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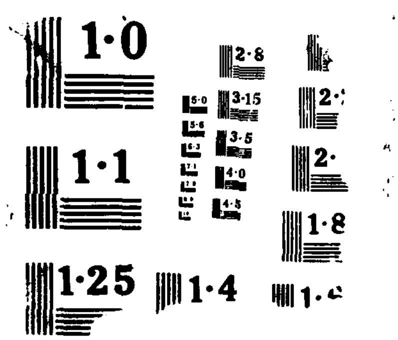
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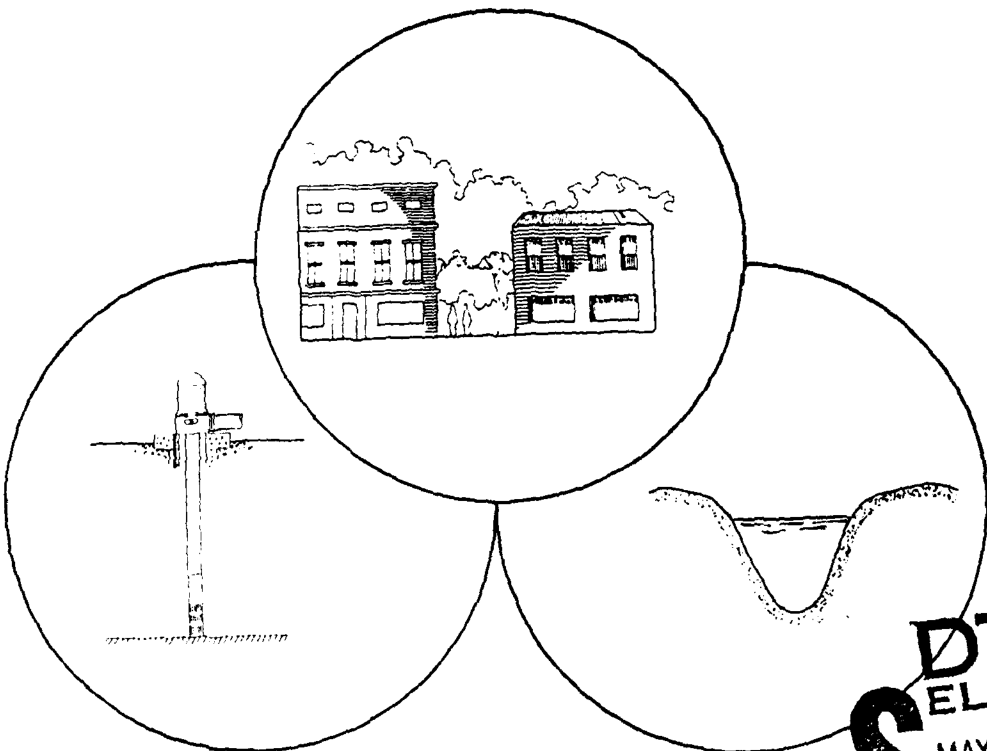
ELEMENTS OF CONJUNCTIVE USE WATER SUPPLY



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MARCH 1988

The Hydrologic Engineering Center
Water Resources Support Center
U.S. Army Corps of Engineers

ELEMENTS OF CONJUNCTIVE USE WATER SUPPLY

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PREFACE

Conjunctive use water supply refers to the coordinated use of both surface water and groundwater to meet water supply needs. This coordination can take on many forms. It can be managerial where both surface water and groundwater are withdrawn in a coordinated manner; physical where the two resources are hydraulically interconnected; and legal where the use of one conserves the other for another time. What is common is the conjunctive use of both resources to meet water supply needs.

There are many elements or tasks associated with conjunctive use planning. They range from the hydrology and hydraulics of the resources themselves to the legal rights associated with their use. This document is intended as a reference to assist those involved in conjunctive use planning to more effectively and quickly focus on the necessary tasks. The major elements are described and important references cited. Because many aspects of conjunctive use are dependent upon site specific details, the descriptions can only serve as a guide, point the direction. To assist in understanding the many elements, case examples of specific projects are presented.

ACKNOWLEDGEMENTS

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CONJUNCTIVE USE IN THE HYDROLOGIC CYCLE

The major characteristics of surface water and groundwater sources are generally well known. Surface waters are available seasonally, but usually with some degree of uncertainty as to time and amount available. However, it is possible to determine the size of surface storage facilities necessary to regulate supply for desired output characteristics, despite the irregular inflow from natural sources (Maknoon and Burges, 1978). Surface storage facilities are characterized by rapid fill up, evaporation, seepage losses, and high initial costs. On the other hand, groundwater is usually available in vast quantities in large aquifers, with little variation in time, hence causing less uncertainty in availability prediction than that of surface water.

The importance of conjunctive use lies in the interaction between the two characteristically different water sources. This interaction is part of the hydrologic cycle, as shown in Figure 1. In this figure, specific features of conjunctive use are noticeable such as natural replenishment, artificial recharge, return flow from irrigation and sewage, and stream-aquifer interaction. There are two main aspects of this interaction: the flow of groundwater to support river flow and the flow from the river to the groundwater. The former is a common occurrence in temperate regions, whereas the latter occurs widely in arid regions. Figure 2 shows a conceptual model that illustrates the interrelationship between surface water and groundwater sources.

River flow is derived essentially from precipitation less evaporation. In a natural river system with negligible abstractions and discharges, there are two main components of river flow: direct runoff and base flow. Direct runoff may be subdivided into channel infiltration, overland flow, and interflow, whereas base flow is that part of river flow that is derived from groundwater. Groundwater flow is defined as the

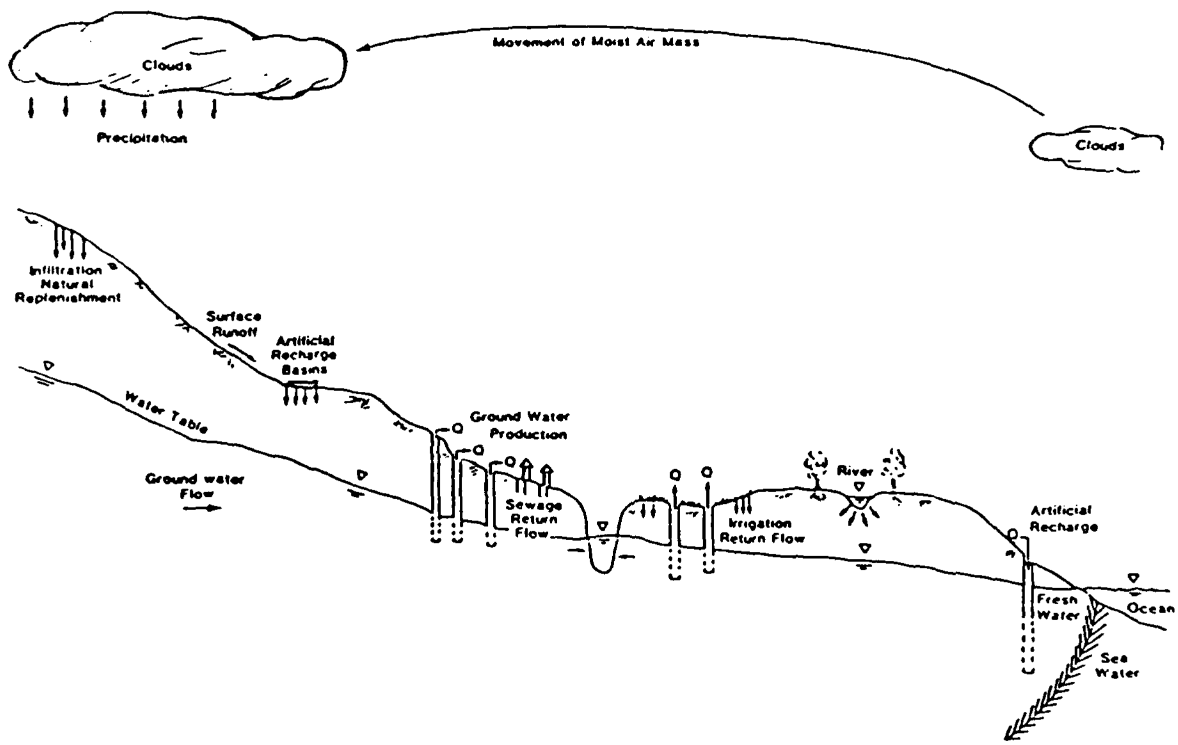

FIGURE 1: Conjunctive Use Components in the Hydrologic Cycle

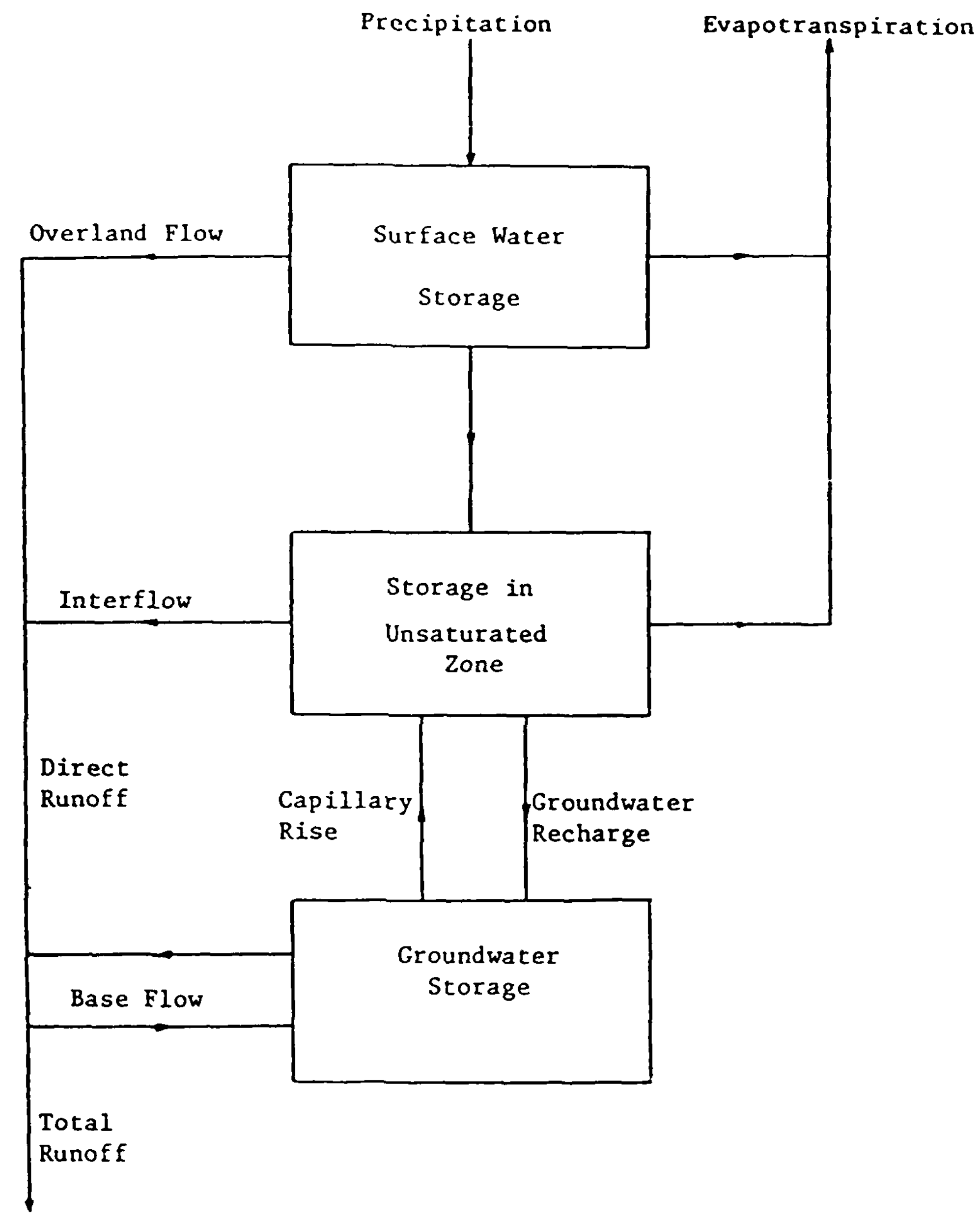

FIGURE 2: Hydrologic Interaction between Surface Water and Groundwater Storages

flow within the saturated zone. In catchments with more than one aquifer, the base flow component may be subdivided according to the contributing geologic formations. The proportion of direct runoff or base flow in total river flow may vary substantially on the basis of time and location, because of the effects of different soil types, geology, land use, topography, stream patterns, and changes in precipitation, evaporation, and temperature.

In temperate regions, groundwater recharge is derived mainly from precipitation less evapotranspiration. However, in arid regions, where annual potential evaporation exceeds precipitation, groundwater recharge is frequently derived from temporary rivers that are in flood. More generally, both flood water and base flow from mountain rivers can recharge aquifers in the foothills and adjacent relatively dry low-lying areas. In addition, groundwater recharge may occur from lakes, canals, excess irrigation, and artificial recharge operations. If the water table is near to the surface of the ground, as in some temperate areas, then the capillary rise may enable evaporation to deplete directly the groundwater storage.

The interaction between surface water and groundwater sources is important in water resource development, because advantage may be taken of differing characteristics to increase yields or improve the quality of water supplies. These differing characteristics may be in storage, flow, and quality of the sources. Changes in one part of the hydrologic cycle may induce beneficial or detrimental changes in another part of the cycle. To study and analyze these changes as they relate to conjunctive use, one needs to study the groundwater balance.

GROUNDWATER COMPONENTS

Water balance is defined by the hydrologic equation, which is basically a statement of the law of conservation of matter as applied to the hydrologic cycle. The hydrologic equation states that in a specified period of time all water entering a specific area must either go into storage within its boundaries, be consumed, be exported, or flow out. For groundwater flow, the hydrologic equation is a specialized form of balance that requires quantification for all items of inflow to and outflow from an aquifer, as well as storage changes in the aquifer. Few of these items may be measured directly, some can be determined by differences between measured volumes or rates of flow of surface water or other water bodies, and some may be estimated. Factors affecting the groundwater balance may be expressed in the following general form:

Groundwater inflow*				Groundwater outflow*
Natural replenishment*				Leakage
Return flows from irrigation and sewage*	------>	Change in groundwater storage	------>	Evaporation
Artificial recharge*				Pumpage and drainage*
Inflows from surface water bodies*				

in which factors that may be affected by a conjunctive use operation are marked by an asterisk and discussed in this report.

a. <u>Groundwater flow</u>: When a boundary of an aquifer is pervious, groundwater may enter and exit the aquifer through it. The rate and direction of flow are governed by the gradient of the water table or piezometric surface along the boundary, as well as the characteristics of the porous medium.

b. <u>Natural replenishment</u>: The main source of groundwater recharge is generally from precipitation, particularly in those areas where annual average precipitation exceeds potential evaporation. Evaporation may decrease water held in surface storage, as shown in Figure 2. Groundwater recharge occurs when precipitation less actual evaporation (the residual precipitation) has infiltrated to the water table. This may occur from several hours to several months after the occurrence of precipitation. If the precipitation is in the form of snow, then infiltration is delayed indefinitely until the snow melts.

The relationship between natural replenishment and precipitation is governed by, but not limited to, the following factors (Bear, 1979): type of precipitation, climatic conditions, soil moisture prior to the storm, storm characteristics (duration, intensity, and peak intensity), topography of the ground surface, perviousness of the ground surface, and vegetation cover.

Infiltration can be defined as the unsaturated downward flow from the ground surface to the water table. The theory of infiltration is discussed by Philip (1957), Bear (1979), Hillel (1980a), and others. However, the use of theory by itself may not be a practical way to determine the rate of natural replenishment of an aquifer, as it requires detailed information on soil characteristics along the vertical direction. In addition, for the purpose of management of a groundwater system, and considering the large volume of water stored in an aquifer at any time, one is not interested in the variability of infiltration during any individual storm. Similarly, one is not interested in the variability of infiltration resulting from storms during the year (taking each storm as an instantaneous pulse). One is, however, interested in annual or seasonal replenishment in most regional management studies. It is often assumed that natural replenishment is distributed uniformly throughout the year or throughout the rainy season. Methods for

throughout the year or throughout the rainy season. Methods for estimating natural replenishment are discussed in a following section.

c. Return flows from irrigation and sewage: In general, in irrigation practices not all water is used up as consumptive use; a portion of it infiltrates, eventually reaching the water table. This portion of irrigation water may be called return flow. It may be due to excess irrigation water because of a lack of management or due to over-irrigation to leach salts from the root zone. In the latter case, when an aquifer underlies the irrigated land and when there is no adsorption or other modifying phenomena, the leached salts eventually reach the underlying aquifer.

In addition to irrigation return flows, reclaimed wastewater constitutes another source of water for recharging groundwater. As conservation, reclamation, and reuse of water are receiving increasing emphasis, wastewater recharge is practiced in a variety of ways throughout the world. Septic tanks can act as small recharge units. Furthermore, irrigation with treated wastewater has become a common practice. The quality problem associated with return flow and leaching, however, should be carefully studied when wastewater is used for irrigation.

d. Inflows from surface-water bodies: Hydraulic connections between surface-water bodies (such as streams, canals, and lakes) and aquifers have similar characteristics. For the purposes of this report, a stream-aquifer system is considered. If a stream is underlain by an unconfined aquifer, water movement may be from the stream to the aquifer or vice versa. Most perennial streams flow toward adjacent or underlain aquifers and are called influent streams. On the other hand, much of the low water flow in streams is derived from aquifers whose water tables are at a higher elevation than the water levels in the streams. These streams are called effluent streams.

In a conjunctive use operation of surface water and groundwater, knowledge of the rate, amount, and direction of water flow between the two sources is important. The rate, amount, and direction of flow depend on the hydraulic conductivity of the streambed, the unsaturated soil-water characteristics, the aquifer parameters, and the hydraulic gradient of the flow. Once the rate and direction of flow are known, a model of a stream-aquifer system can be used to predict future water supplies of both sources used conjunctively. In such a model, the stream can be represented as a boundary of specified heads or as a source. If the stream has a large flow rate, however, the lateral flow between the stream and the aquifer (and even the interflow) does not affect the streamflow for all practical purposes and, for that matter, the depth of flow. On the other hand, in a stream with a small flow, the exchange of water is of utmost importance to the streamflow. Both base flow and interflow contribute significantly to the small streamflow.

e. <u>Pumpage and drainage</u>: Important elements in conjunctive use of surface water and groundwater are the methods of water withdrawal and the rates of withdrawal from an aquifer system. Water withdrawal is usually done by shallow and deep vertical wells, horizontal or radial collector wells, and galleries. Design and construction of wells are discussed by American Water Works Association (1958) and Marino and Luthin (1982). Drainage systems are usually installed to control the elevation of the water table and to remove salts that have been flushed down to the water table (Luthin, 1966; Marino and Luthin, 1982). It should be noted that in a conjunctive use study one is interested in a regional water balance. Thus, knowledge on the total water withdrawn by pumpage and drainage is sufficient.

GROUNDWATER FLOW

In a conjunctive use study, it is of prime interest to have some knowledge of the general direction and rate of groundwater flow. In a simplified manner, the aquifer can be idealized as one having a horizontal base and vertical walls, where appropriate. The flow rate Q (volume per unit time) in this system can then be estimated by the Darcy equation (Marino and Luthin, 1982):

$$Q = \frac{KA(h_1 - h_2)}{L} \tag{1}$$

in which K is the hydraulic conductivity of the aquifer material; A is the cross-sectional area of the flow; h_1 and h_2 are piezometric heads at sections 1 and 2 in which the flow is taking place; and L is the length of the flow path. The parameters of this equation can be obtained as follows. The hydraulic conductivity is usually estimated via aquifer tests (e.g., Bouwer, 1978; Marino and Luthin, 1982). Of course, values of hydraulic conductivity can be obtained from past studies conducted by government agencies and/or private consultants. The cross-sectional area of the flow and the length of the flow path are estimated from geologic data. Finally, the piezometric heads are measured at new or existing boreholes or test wells.

This simplified method offers a first-cut estimate of the direction and the rate of flow, which may be sufficient for a regional study. However, if more detailed information is needed, one can use numerical methods (e.g., link-node, finite-difference, or finite-element methods) to solve the partial differential equation governing the flow in the aquifer system, subject to appropriate boundary conditions. These methods are particularly useful when the aquifer is heterogeneous, the rate of flow varies with time, and the aquifer geometry is complex. The equation governing the flow, which can be derived by using

the law of conservation of matter, can be expressed as (Bear, 1979; Marino and Luthin, 1982)

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial \Phi}{\partial z}\right) = S_s \frac{\partial \Phi}{\partial t} \qquad (2)$$

in which K_x, K_y, and K_z are the hydraulic conductivities of the aquifer in the x, y, and z directions, respectively; is the piezometric head; and S_s is the specific storativity, also called the specific storage or the storativity of the medium (the volume of water that a unit bulk volume of the aquifer releases from or adds to storage per unit decline or rise of head), which can be obtained from aquifer tests or studies previously conducted in the study area. In addition, values of K_x, K_y, and K_z may be difficult or impossible to estimate. Thus, it is usually assumed that $K_x = K_y = K_z = K$ (i.e., the aquifer is assumed isotropic) and K can then be obtained as explained earlier. There are several numerical simulation models that can be used to solve equation (2) subject to different boundary conditions (Trescott and Larson, 1977; Gupta et al., 1984).

NATURAL REPLENISHMENT

In a conjunctive use study, a significant input to the aquifer system is the rate and amount of water replenished. This replenishment can be by natural or artificial means. Several methods can be used to estimate natural replenishment from annual or seasonal precipitation. For example, natural replenishment can be regarded as an aquifer parameter (rather than related to precipitation) whose value can be estimated by using parameter estimation techniques (see, e.g., Bear, 1979). Natural replenishment can also be estimated by using a water balance model in which average annual infiltration is equal to the algebraic sum of average annual groundwater runoff, average annual surface retention loss, and average annual total evapotranspiration (Caro and Eagleson, 1981). When the recharge is derived from spreading basins, the recharge or infiltration rate through the unsaturated zone may be estimated by using the Green and Ampt (1911) equation:

$$w = \frac{K(\theta)\,[H_c + H + z_f]}{z_f} \tag{3}$$

in which $K(\theta)$ is the unsaturated hydraulic conductivity; H_c is the effective capillary drive (a measure of the soil capillary suction); H is the depth of water in the basin (or river, canal, etc.); and z_f is the depth of the sharp wetting front. The soil hydraulic conductivity can be measured by laboratory or field techniques (Hillel, 1980a). For most soils, H_c will rarely exceed 10 inches and is very quickly negligible compared to z_f. If H is significant (say, H > 1 ft), then H_c becomes insignificant (Morel-Seytoux and Khanji, 1974; Morel-Seytoux and Verdin, 1981). The recharge or infiltration rate can also be estimated via solution of partial differential equations describing the flow in the unsaturated zone. Some of those

When detailed data on precipitation are available (e.g., from publications of the National Weather Service or the U.S. Geological Survey), one can use digital simulation models to estimate natural replenishment. Some of the models that can be used are the U.S. Army Corps of Engineers Streamflow Synthesis and Reservoir Regulation Model (Rockwood, 1964), the Dawdy and O'Donnell (1965) model, the Stanford Watershed Models (Crawford and Linsley, 1966), and the Hydrocomp Simulation Program (Hydrocomp International, Inc., 1969). As indicated by Bear (1979), these computer models simulate the hydrologic cycle, using a moisture accounting procedure of one form or another. A system of equations describes the interrelationships among the various elements of the model. During the simulation, a running record is maintained of all moisture entering, stored, and leaving the basin as evapotranspiration, surface runoff, and groundwater. The latter is the natural replenishment which is of interest to us in this report.

It should be noted that these simulation models require detailed data on the physical and hydrological conditions of the basin. After proper calibration and verification, the models can be used for prediction purposes (under the same conditions that were used in the calibration phase).

ARTIFICIAL RECHARGE

As defined by Todd (1980), artificial recharge is the augmentation of the natural movement of surface water into underground formations by appropriate methods. These may include spreading of water on the ground, pumping of groundwater to induce recharge from surface water bodies, and recharge through boreholes, wells, mineshafts, or other suitable access features. The approach actually selected for a particular location will depend upon a variety of factors such as topography, geology and soil state, the amount of water to be recharged, and the end use of the water.

The purposes of artificial recharge of groundwater are: to reduce, stop, or even reverse declining groundwater levels; to protect underground freshwater in coastal aquifers against saltwater intrusion from the ocean; and to store surface water, including flood or other surplus water, imported water, and reclaimed wastewater for future use.

An artificial recharge installation may serve more than one purpose. In certain areas, for example, artificial recharge not only adds water to the available groundwater supply but also is a means to dispose of stormwater runoff. In another instance, artificial recharge is a barrier to saltwater intrusion, increases the available supply of fresh water, and decreases a land-subsidence condition that may have been in progress for years.

In conjunctive use of surface water and groundwater, it is not of great interest to differentiate between recharges that occur through structures that were specifically developed for that purpose or accidentally through structures not originally developed for that purpose. Thus, it may be better to use the concept of "managed recharge", which may be defined as any procedure that enables the recharge of groundwater from surface

water sources under controlled environment and management. In fact, in artificial recharge, the recharge process is not artificial but the availability of water at a particular time and location is artificial.

The advantages of artificial recharge in a conjunctive-use operation may be partially outweighed by certain disadvantages (Buchan, 1958): (1) not all added water may be recoverable; (2) the area required for operation and maintenance of a groundwater supply system (including the groundwater reservoir itself) is generally larger than that required for a surface-water supply system; (3) salts of calcium, magnesium, iron, manganese, or other elements in the recharge water cannot be readily removed; (4) clogging of aquifers is difficult to remedy; (5) sudden water supply demands may not be met because groundwater reservoirs are not as easily drained as their surface water counterparts; and (6) expansion of groundwater public supply systems may be costly.

Artificial recharge can be implemented by several methods, the most widely practiced of which is water spreading. The choice of method for a particular case depends on the source of water, the quality of the water, the type of aquifer, the topographical and geological conditions, the type of soil, economic conditions, and so forth. Artificial recharge methods are discussed by Bauman (1965), Todd (1980), Huisman and Olsthoorn (1983), and Oaksford (1985). This report briefly discusses the applicability, advantages, and disadvantages of each method. Following Oaksford (1985), artificial recharge methods may be classified as direct-surface, direct-subsurface, combination of surface-subsurface, and indirect techniques.

a. Direct-surface recharge: In these methods, water is applied to the ground surface and moves through the soil until reaching the aquifer. The most important factors governing the amount of water reaching the aquifer are the size of the recharge area and the length of time that water is in contact with the

soil. The following techniques have been widely used: flooding, ditch and furrow systems, spreading basins, stream-channel modification, streamflow augmentation, and overirrigation.

Flooding. The objective is to spread the water over a large area with a shallow depth that travels slowly without disturbing the soil. This technique is applicable in relatively flat topography with high-permeability soils. Compared with other spreading techniques, flooding costs least for land preparation. The biggest problem, however, is the containment of flood water, which should be done by constructing embankments or ditches around the entire flooding area. Other problems are related to large land requirements and evaporation.

Ditch and furrow systems. This technique distributes the recharge water in a series of ditches, or furrows, that are shallow, gently sloped, and closely spaced to obtain maximum contact area. Three general patterns are usually practiced (Todd, 1980): (1) lateral, where a series of small ditches extend laterally from the main canal; (2) dendritic, where the main canal successively branches into smaller canals and ditches; and (3) contour, where the ditch follows the ground contour and by means of sharp switchbacks meanders back and forth across the land. The method is adaptable to irregular terrain but seldom provides water contact to more than about 10 percent of the gross area. The advantage of this technique is apparent where recharge water contains high loads of suspended sediment with flow rates sufficient to carry a large percentage of foreign materials through the system and back into the source stream. However, if the gradients and flow rates of major feeder ditches are not sufficient to carry suspended material through the system, the deposition of fine-grained material clogs the soil surface openings.

Basins. Water may be recharged by releasing it into basins that are formed by excavation or by construction of dikes or

small dams. Horizontal dimensions of such basins vary from a few feet to several hundred feet. The most common system consists of individual basins fed by water pumped from nearby surface sources.

Because of their general feasibility, efficient use of space, and ease of maintenance, basins are the most favored method of artificial recharge. Perhaps, the main disadvantage of spreading basins is the clogging of bottom surfaces. Silt-free water aids in preventing sealing of basins during submergence. Most basins require periodic maintenance to improve infiltration rates by scraping the bottom surface when dry. The infiltration capacity of basins can also be improved by soil treatment, vegetation, or special operating procedures (Schiff, 1955).

Stream-channel modification. This method consists of altering a natural stream channel to increase the time and area over which water is recharged from a naturally losing channel (Todd, 1980; Oaksford, 1985). Most stream-channel modification structures are designed to increase recharge only seasonally. Many are destroyed by floods. Nevertheless, stream-channel modification is effective where suitable, because construction costs are relatively low, maintenance is inexpensive, and the procedure hardly conflicts with other land uses.

Streamflow augmentation. This method involves the application of recharge water to a stream channel near the head of its drainage area to reestablish or increase infiltration through the streambed. The method is especially suitable for areas where streams fed by groundwater have ceased to flow or have become dry in their upper reaches, because of lowered groundwater levels. Among the disadvantages of this method is the low efficiency compared to other techniques and the fact that economical sources of recharge water may not always be available. However, the advantage of this method is the restoration of stream ecosystems and the resulting aesthetic features.

Over-irrigation. During the dormant, winter or non-irrigating seasons, irrigation water may be applied to artificially recharge the groundwater. Most of the artificial recharge methods may be used, especially the first four techniques described earlier. Over-irrigation requires no additional cost for land preparation because the distribution system is already installed. However, it is important to consider side-effects of this method such as leaching and waterlogging of soils, as well as physical or legal limitations on pumpage.

b. Direct-subsurface recharge: These methods include techniques by which the recharge water is conveyed and joined to the groundwater. They are generally used in areas where a geologic formation (such as an impermeable or semipermeable confining stratum) separates the source of recharge water from the aquifer requiring replenishment. Some direct-subsurface recharge techniques will be discussed next. All of these techniques use structures that occupy much less land than those of direct-surface recharge methods.

Natural openings. This method takes advantage of fractures that exist in the porous material to drain water from an impoundment and deliver it to the aquifer. The technique may need maintenance and improvement, depending on the source of water and the size, configuration, and location of the fractures.

Pits and shafts. In areas where there is a confining stratum that restricts the downward passage of water, recharge may be done through pits or shafts penetrating the confining layer. The technique works best where the impervious layer is not too far below the ground surface. Pits do not necessarily have to be constructed for recharge purposes; abandoned gravel pits or quarries may be used. Shafts, which are deeper and smaller in diameter than pits, are used for penetrating deeper strata. Unlike wells, shafts do not penetrate the aquifer

itself. This is why shaft fill material must be changed periodically to upgrade the infiltration rate that is decreased due to clogging. The major disadvantage of this method is the high cost of excavation, which can be overcome if abandoned pits are used.

Reverse drainage. This method uses the principles of drainage to pipe water into a perforated drainage conduit from which water infiltrates the soil. The primary advantage of this method is its negligible effect on surface land use (Oaksford, 1985). Thus, application of this method may be desirable in areas where land is very expensive (Whetstone, 1956; Asano, 1980).

Recharging wells. This method is generally used to replenish water to deep confined aquifers with low-permeability material, or when there is space limitation for the use of surface techniques to replenish an unconfined aquifer, such as in urban areas. In coastal aquifers, injection or recharge wells are also used to inject freshwater to retard or prevent the further movement of saltwater inland.

The major disadvantage of this technique is the clogging of well screens due to: (1) fine silty material suspended in the source water; (2) large amounts of dissolved air carried with the recharge water; and (3) bacteria carried in the source water that grows on the screen or the surrounding formations. As discussed by Todd (1980), there are methods to partially prevent these clogging problems.

Recharge wells are advantageous because of their little space requirements and ability to replenish two or more aquifers simultaneously. Also, recharge wells represent one of the best methods to prevent saltwater intrusion. Furthermore, they are convenient means for disposal of septic tank effluent, excess

irrigation water, and surface runoff into deep permeable volcanic terrains.

c. <u>Combination of surface-subsurface recharge</u>: Among the direct-surface and direct-subsurface recharge methods, there are techniques that can be used in combination to gain new characteristics and more efficiency. As discussed by Oaksford (1985), two of these techniques are subsurface drainage collectors with wells and spreading basins with pits, shafts, or wells.

d. <u>Indirect recharge</u>: These methods do not directly recharge or increase the amount of water in storage but allow an increased rate of groundwater withdrawal from an aquifer (Buchan, 1958). Indirect recharge methods include induced surface-water recharge and aquifer modification.

<u>Induced surface-water recharge</u>. This method is used in shallow high-permeability aquifers that are hydraulically connected to a body of surface water such as a river or lake. The withdrawal installations (e.g., wells and drainage galleries) are located at a relatively small distance from the source of surface water (e.g., a river or a lake) and parallel to it. Withdrawal of water through these installations causes a lowering of the water table (the hydraulic gradient slopes away from the river and towards the installation), thus inducing the movement of water from the surface-water source to the aquifer for further withdrawal. This action is of course possible if there is a relatively good hydraulic connection between the surface-water source and the aquifer system. Often there are silt deposits that decrease the hydraulic conductivity of the streambed. This can be avoided by placing pumping facilities near stream reaches with adequate velocities to prevent deposition of material.

As indicated by Oaksford (1985), the amount of surface water that can be induced to recharge an aquifer depends on: (1) the

amount and proximity of surface water; (2) the hydraulic conductivity of the aquifer; (3) the area and hydraulic conductivity of the streambed; and (4) the hydraulic gradient created by pumping.

Aquifer modification. There are several techniques by which an aquifer can be modified to impede outflow or create additional storage capacity. A technique that has been used in India (Ratnoparkhi, 1978) and North Dakota (Pettyjohn, 1981) consists of building a groundwater barrier to obstruct and detain groundwater flow. In addition, a natural-drainage channel can be lined, filled with clean uniform sand, and covered with gravel mulch to provide a storage system that supplies filtered water under gravity flow and is protected against excessive evaporation losses (Helweg and Smith, 1978).

In summary, the conditions and factors required for successful artificial recharge of groundwater depend on a hydrogeologic study of the specific site. The surface and subsurface geology of the site and the relationship of geology to the configuration of the aquifer dictate an optimum recharge site in the basin. Because land areas are overlain by valuable agricultural and urban developments, the cost and ability to acquire land and to access it to rechargeable surface water often outweigh the geologic and hydraulic acceptability of the site. In general, the selection of a site for artificial recharge operations depends on factors such as hydrogeologic characteristics, topography and streamflow, water supply characteristics, legal aspects, availability of land, land use in adjacent areas, and public acceptance. Cehrs et al. (1980) discuss in detail geologic factors that affect the selection of a site. Oaksford (1985) discusses the selection of a particular method for a specified site.

ESTIMATING STREAM-UNCONFINED AQUIFER FLOW

In conjunctive use planning one often encounters a situation in which an aquifer system is in direct hydraulic connection with adjacent streams. The streams may be influent or effluent, or both, depending on the prevailing hydraulic gradient. If one of the streams is influent while the other is effluent, the inflow to the aquifer system may be from natural or artificial surface recharge, irrigation or sewage return flows, or from the influent stream. On the other hand, if both streams are effluent, the inflow may be from natural or artificial surface recharge or from irrigation or sewage return flows. Consider the stream-aquifer system shown in Figure 3, in which the aquifer is receiving uniform vertical recharge at a rate w per unit area (as may occur in maritime climates with long periods of low-intensity rain and in large irrigated areas during the irrigation season). The recharge can be from excess rainfall, deep percolation from irrigation, or other water seeping down in the unsaturated zone. The equation governing the steady-state flow in this case is (Marino and Luthin, 1982):

$$\frac{d^2h^2}{dx^2} + \frac{2w}{K} = 0 \tag{4}$$

with boundary conditions

$$h(0) = h_1 \text{ and } h(\ell) = h_2 \tag{5}$$

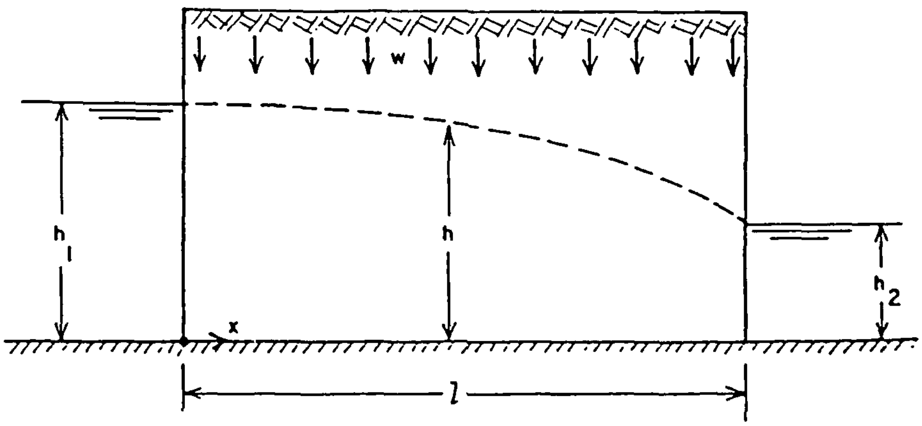

FIGURE 3: Stream-unconfined Aquifer System Receiving Uniform Vertical Recharge (Marino and Luthin, 1982)

The piezometric head at any point in the aquifer is given by the expression

$$h^2(x) = h_1^2 + \frac{wx(\ell - x)}{K} - \frac{(h_1^2 - h_2^2)x}{\ell} \tag{6}$$

The maximum height of the water table (h_{max}), which occurs at the water divide x_{max}, can be expressed by:

$$h_{max}^2 = \left(\frac{h_1^2 + h_2^2}{2}\right) + \frac{w\ell^2}{4K} + \frac{K}{4w\ell^2}(h_1^2 - h_2^2)^2 \tag{7}$$

and

$$x_{max} = \left(\frac{\ell}{2}\right) - \left(\frac{K}{2w\ell}\right)\ (h_1^2 - h_2^2) \tag{8}$$

At the water divide there is no flow since the water table is horizontal. The rate of flow at any point in the aquifer can be calculated by using the Darcy equation. In equations (5)-(8), h_1 and h_2 are average depths of water in the streams during the period of study. Hourly, daily, and monthly records of stream stage are usually available from the U.S. Geological Survey. The length or width of the aquifer, ℓ , is the average distance between the streams and can be estimated from elevation contour maps of the area. The recharge rate, w, can be estimated by using the water balance model of Caro and Eagleson (1981) or by using equation (3).

When the recharge rate is not uniform, but varies with time, and the flow in the stream-aquifer system is time-dependent (transient), the height of the water table can be calculated with a more complex equation presented by Marino and Luthin (1982).

The maximum height of the water table and its location may be used to ascertain potential problems of water logging and salinity that may result from the recharge practice.

ESTIMATING STREAM-LEAKY AQUIFER FLOW

In some instances one encounters a leaky aquifer system that is hydraulically connected to adjacent streams. In these cases, the flow system is more complex than the one examined earlier and the number of hydraulic parameters is also greater. One is still, however, interested in finding the effects of recharge on the water table. Specifically, one is interested in the distribution of the water table and the piezometric surface to ascertain the direction and rate of vertical leakage through the aquifer system (Marino and Luthin, 1982). A schematic representation of such flow system is shown in Figure 4. Notice that when a leaky unconfined aquifer receiving uniform vertical recharge rests on a semipervious stratum with low resistance to vertical flow, one must consider the simultaneous flow taking place in both unconfined and confined aquifers (Huisman, 1972; Marino and Luthin, 1982). Let the transmissivities of the unconfined and confined aquifers be considered constant and respectively denoted by T_1 and T_2, where by definition $T = Kb$. Similarly, let the leakage factors of the unconfined and confined aquifers be respectively denoted by B_1 and B_2, where by definition

$$B = \left[\frac{T}{\left(\frac{K'}{b'}\right)}\right]^{\frac{1}{2}}.$$

If not available from previous studies, the values of T_1 and T_2 can be estimated from aquifer tests. The average thicknesses of the confined aquifer, b, and semipervious layer, b', can be estimated from well logs or subsurface geology maps of the area, usually available from the U. S. Geological Survey or from state and local water agencies. Mathematically, this flow situation can be represented by (Marino and Luthin, 1982):

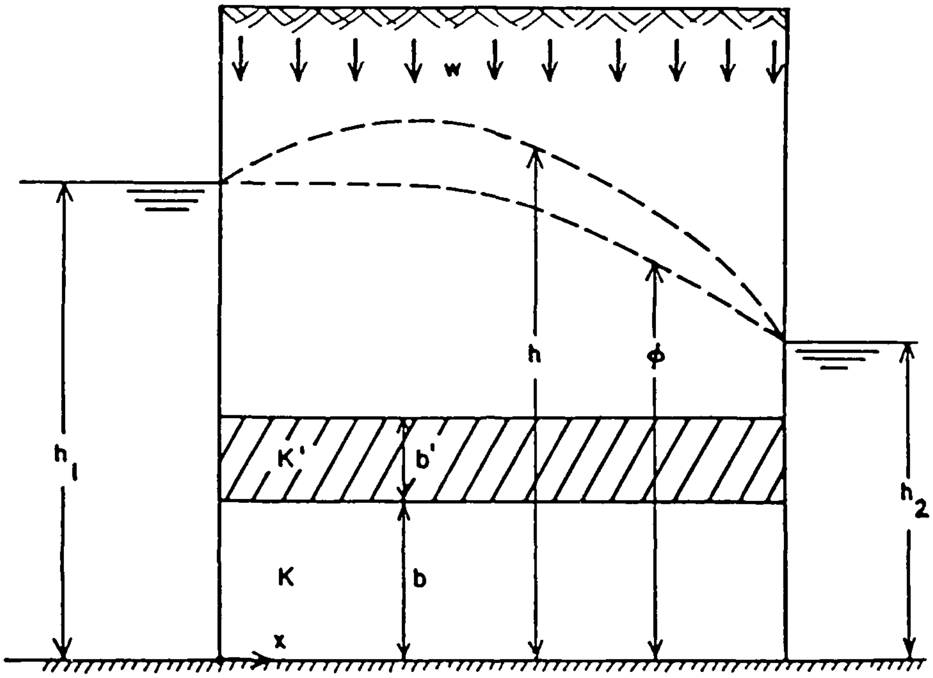

FIGURE 4: Stream-leaky Aquifer System Receiving Uniform Vertical Recharge (Marino and Luthin, 1982)

$$\frac{d^2h}{dx^2} - \frac{(h - \phi)}{B_1^2} + \frac{W}{T_1} = 0 \tag{9}$$

and

$$\frac{d^2h}{dx^2} + \frac{(h - \phi)}{B_2^2} = 0 \tag{10}$$

subject to the boundary conditions

$$h(0) = \phi(0) = h_1 \text{ and } h(\ell) = \phi(\ell) = h_2 \tag{11}$$

The distribution of the water levels in the unconfined and confined aquifers are:

$$h(x)=h_1-(h_1-h_2)\frac{x}{\ell} + \frac{W\tau x(\ell-x)}{2(1+\tau)T_1} - \frac{W\beta^2}{(1+\tau)T_1}\left[\frac{e^{(\ell-x)/\beta}+e^{x/\beta}}{e^{\ell/\beta}+1}-1\right] \tag{12}$$

and

$$\phi(x)=h_1-(h_1-h_2)\frac{x}{\ell} + \frac{W\tau x(\ell-x)}{2(1+\tau)T_1} + \frac{W\beta^2}{(1+\tau)T_1}\left[\frac{e^{(\ell-x)/\beta}+e^{x/\beta}}{e^{\ell/\beta}+1}-1\right] \tag{13}$$

in which

$$\tau = \frac{T_1}{T_2} \text{ and } \frac{1}{\beta^2} = \frac{1}{B_1^2} + \frac{1}{B_2^2}$$

The flow rate in either unconfined or confined aquifer can be calculated by using the Darcy equation.

ESTIMATING WELL-UNCONFINED AQUIFER FLOW

In a conjunctive use study one may also be interested in analyzing the effect of recharge on the water table while a well is abstracting water from the aquifer. This situation often occurs in agricultural lands in which irrigation water is supplied from an underlying aquifer while the aquifer is recharged from excess irrigation water. The aquifer may be hydraulically connected to one or more streams. If the stream is far enough from the well so that it does not interfere with the flow pattern in the vicinity of the well or if a stream does not exist at all, then the aquifer can be considered to be areally infinite. Figure 5 shows a well fully penetrating an extensive unconfined aquifer that is receiving uniform vertical recharge at a rate w per unit area. Groundwater movement in the flow system under consideration can be represented by

$$\frac{d}{dr}\left(rh\frac{dh}{dr}\right) + \frac{2w}{K} = 0 \tag{14}$$

subject to the boundary conditions

$$h(r_e) = h_e \text{ and } h(r_w) = h_w \tag{15}$$

in which r_e is the radius of influence of the well (i.e., the radial distance from the center of the well at which the initial height of the water table, h_e, is not affected by the pumpage) and r_w is the radius of the well. As usual, the height of the water table is measured at observation (non-pumping) wells. The height of the water table can be expressed by the relation (Marino and Luthin, 1982):

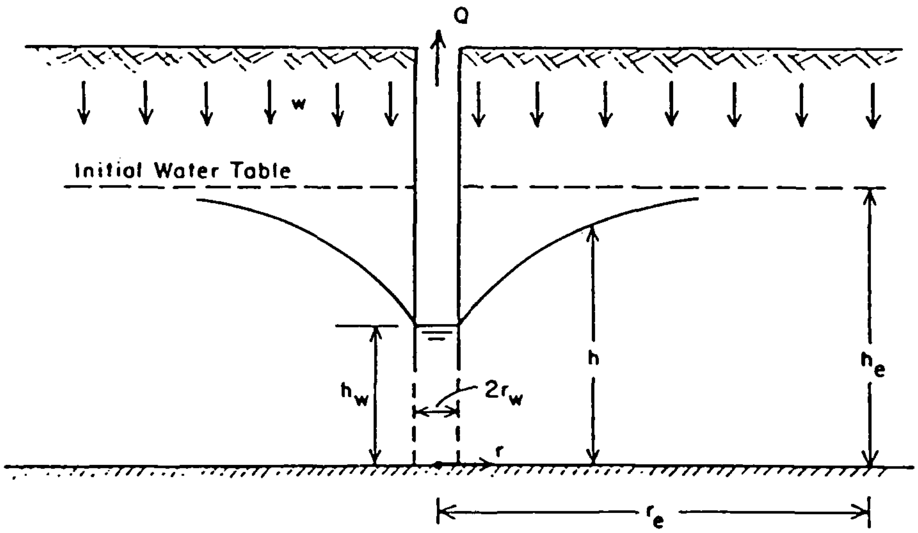

FIGURE 5: Flow to a Well in an Unconfined Aquifer Receiving Uniform Vertical Recharge (Marino and Luthin, 1982)

$$h^2(r)-h_w^2 = [h_e^2-h_w^2+(\frac{W}{2k})(r_e^2-r_w^2)]\frac{\ell n(r/r_w)}{\ell n(r_e/r_w)} - \frac{W(r^2-r_w^2)}{2K} \quad (16)$$

Assuming that

$$r_e^2 >> r_w^2,$$

the discharge rate Q at some radial distance r can be expressed as

$$Q = \pi K[\frac{h_e^2 - h_w^2 + (W/2K)r_e^2}{\ell n(r_e/r_w)}] - W\pi r^2 \quad (17)$$

If the unconfined aquifer is bounded by vertical impermeable boundaries (Figure 6), i.e., a well discharging from a closed unconfined aquifer is in balance with uniform vertical recharge, the drawdown at the well can be approximated by the relation (Marino and Luthin, 1982):

$$h_e^2 - h_w^2 = (\frac{Q}{\pi K})\ell n(\frac{r_e}{r_w}) - (\frac{W}{2K})(r_e^2 - r_w^2) \quad (18)$$

Assuming that

$$r_w^2 << r_e^2,$$

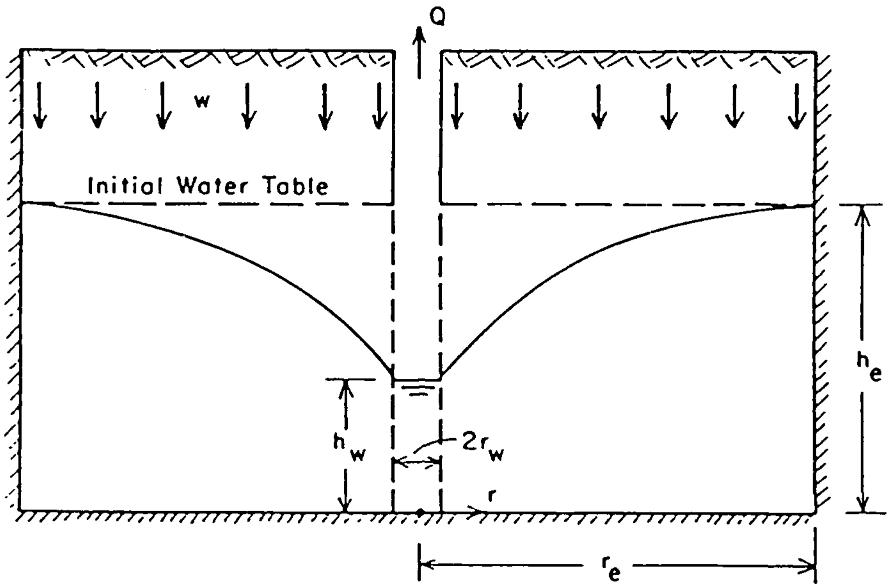

FIGURE 6: Flow to a Well in Balance with Uniform Vertical Recharge in a Closed Aquifer (Marino and Luthin, 1982)

the discharge rate Q can be approximated by:

$$Q = \frac{\pi K h_e^2 [1 - (h_w/h_e)^2]}{\ell n (r_e/r_w) e^{-1/2}} \tag{19}$$

Various other situations that consider recharge in stream-aquifer systems and well-aquifer systems are discussed by Marino and Luthin (1982) and Huisman and Olsthoorn (1983).

ESTIMATING INDUCED RECHARGE

Induced surface-water recharge can take place in shallow highly-permeable aquifers that have a good hydraulic connection with a nearby stream, lake, or canal. Several scenarios of recharge can be considered such as a single pumping well near a stream or a series of wells parallel to a stream. In the case of a single well (Figure 7), the water table elevation is computed with the equation (Huisman and Olsthoorn, 1983):

$$h^2 - h_1^2 = \frac{2qx}{K} - \frac{Q}{2\pi K}\ln\left[\frac{(\ell + x)^2 + y^2}{(\ell - x)^2 + y^2}\right] \tag{20}$$

in which q is the flow per unit width of aquifer and Q is the discharge of the well. The slope of the water table perpendicular to the shoreline can be calculated with

$$\frac{\partial h}{\partial x} = \frac{q}{Kh} - \frac{Q}{2\pi Kh}\left[\frac{\ell+x}{(\ell+x)^2+y^2} + \frac{\ell-x}{(\ell-x)^2+y^2}\right] \tag{21}$$

The rate of induced recharge is highest at x = 0 and y = 0:

$$\frac{\partial h}{\partial x} = \frac{q}{Kh_1} - \frac{Q}{\pi K h_1 \ell} \tag{22}$$

According to equation (22), the recharge is induced from the stream when

$$Q > \pi \ell q.$$

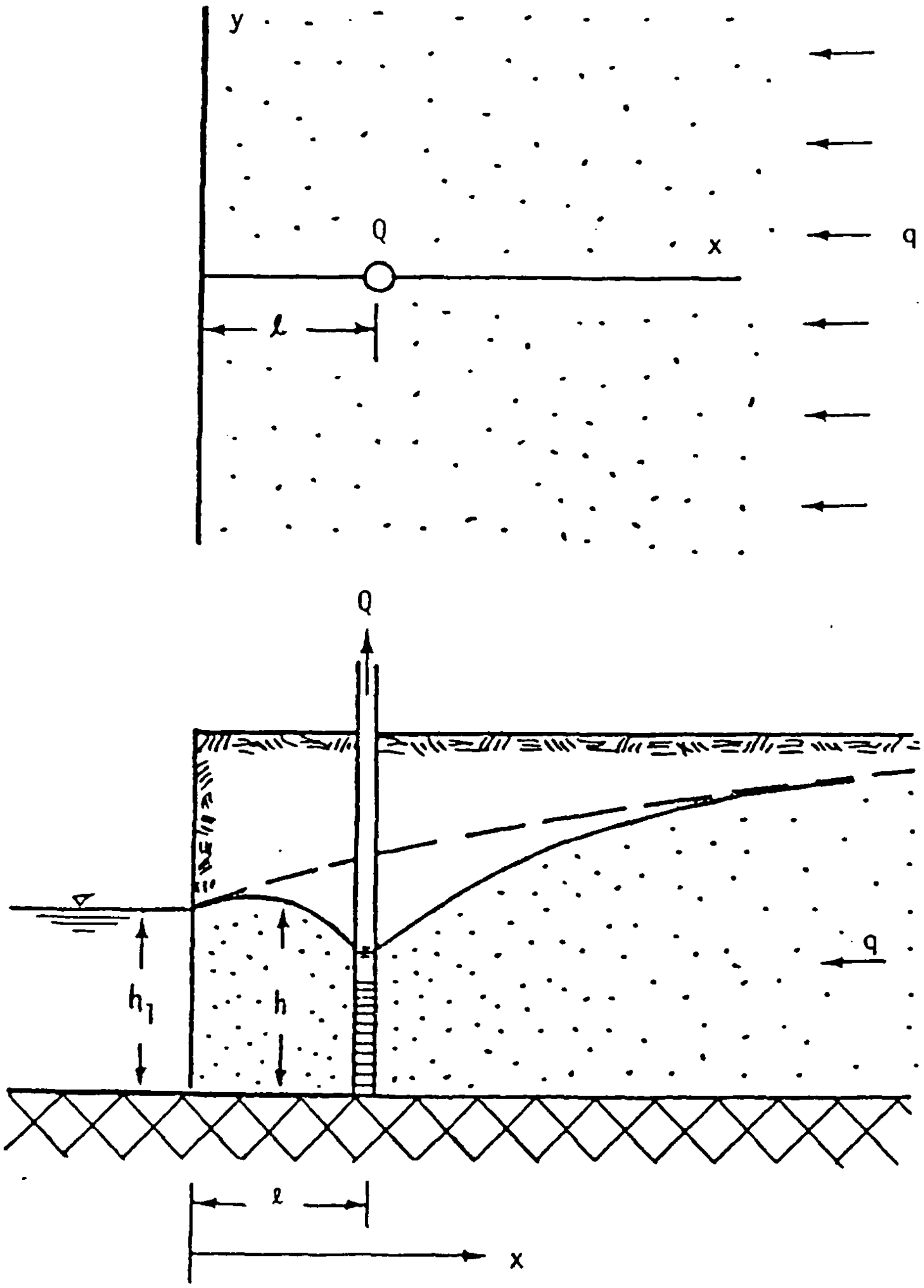

FIGURE 7: Single Well Near a Stream
(Huisman and Olsthoorn, 1983)

When large amounts of water are needed, a series of wells parallel to the streambed must be used. In this situation, the lowering of the water table and the rate of induced recharge depend on the spacing of the wells and their distance from the stream, as well as other factors that are commonly considered in a well system. The solution to this flow problem is presented in Huisman and Olsthoorn (1983).

INFLOWS FROM SURFACE WATER BODIES

The theory of hydraulic and hydrologic relations between surface water and groundwater bodies has been presented by various investigators (Bouwer, 1965, 1969; Hantush, 1965; Jenkins, 1968; and others). However, in conjunctive use and regional planning studies, one is interested in the type of relationship and the amount and direction of seepage between the two water bodies.

The following typical relationships between groundwater and surface water may be identified: aquifers having no hydraulic connection with a stream; aquifers having a constant hydraulic relationship with a stream; and aquifers having a periodic or intermittent hydraulic relationship with a stream.

There are several methods for estimating the seepage rate. One method (UNESCO, 1983) uses hydrograph analysis of surface water and groundwater regimes for different hydraulic connections. This method requires a large amount of groundwater flow data, which in practice may not be readily available. Another method (Bouwer, 1969) considers three conditions for which the multitude of natural profiles of soil hydraulic conductivity can be reduced for theoretical treatment of seepage flow systems: (a) the soil in which the channel is imbedded is uniform and underlain by more permeable material; (b) the soil in which the channel is imbedded is uniform and underlain by less permeable material; and (c) the soil in which the channel is imbedded is of much lower hydraulic conductivity than the original soil for a relatively short distance normal to the channel perimeter. Bouwer (1969) presented several methods of solution for each of those conditions.

In many field situations, analytical solutions to seepage problems may not be applicable, and one must resort to approximate numerical solutions. Whether one uses a

finite-element, finite-difference, link-node or any other approach, the relationship between a stream and an aquifer is usually considered as either a constant-head or a constant-flux boundary. These are the so-called boundary conditions that are required to solve the partial differential equation describing the flow of groundwater. The type of boundary appropriate to a field problem may require careful consideration. Specifically, one must decide to treat a stream as either a fully penetrating constant-head boundary or, more realistically, as a partially penetrating boundary with a semipermeable streambed. Generally speaking, since the estimation of flux is difficult and in many instances it represents an approximate estimation, a stream is usually considered as a constant-head boundary. However, if the flux is estimated, a constant-flux boundary condition would better represent the stream-aquifer system.

PUMPAGE AND DRAINAGE

The importance of water withdrawal systems such as wells and drains was stressed in a previous section. Illustrative examples of well-aquifer systems were also presented. In agricultural lands, however, one may encounter situations in which the source of irrigation water may be from nearby streams and excess irrigation water recharges the underlying aquifer. In these situations, subsurface drains are installed to prevent water logging and salinity problems. Of interest in these situations is the shape and height of the water table for a given drain spacing and rate of recharge. This section discusses a drainage-flow system receiving recharge from excess irrigation water or natural replenishment.

The problem is to compute the rise in water table for a given rate of rainfall or irrigation, soil hydraulic conductivity, depth and spacing of drains, and depth of underlying impermeable layer (Figure 8). Other factors such as the rate of plant water uptake (in the case of an irrigated land) are usually ignored in a basin-wide analysis so as to simplify the mathematical treatment as well as the difficulty in measuring these factors. Marino and Luthin (1982) present the equation that describes the shape of the water table as

$$\frac{y^2}{s^2 \frac{W}{4K}} + \frac{x^2}{\frac{s^2}{4}} = 1 \qquad (23)$$

which is the equation of an ellipse having semimajor and semiminor axes given by

$$\frac{s}{2} \text{ and } \left(\frac{s}{2}\right)\left(\frac{W}{K}\right)^{\frac{1}{2}},$$

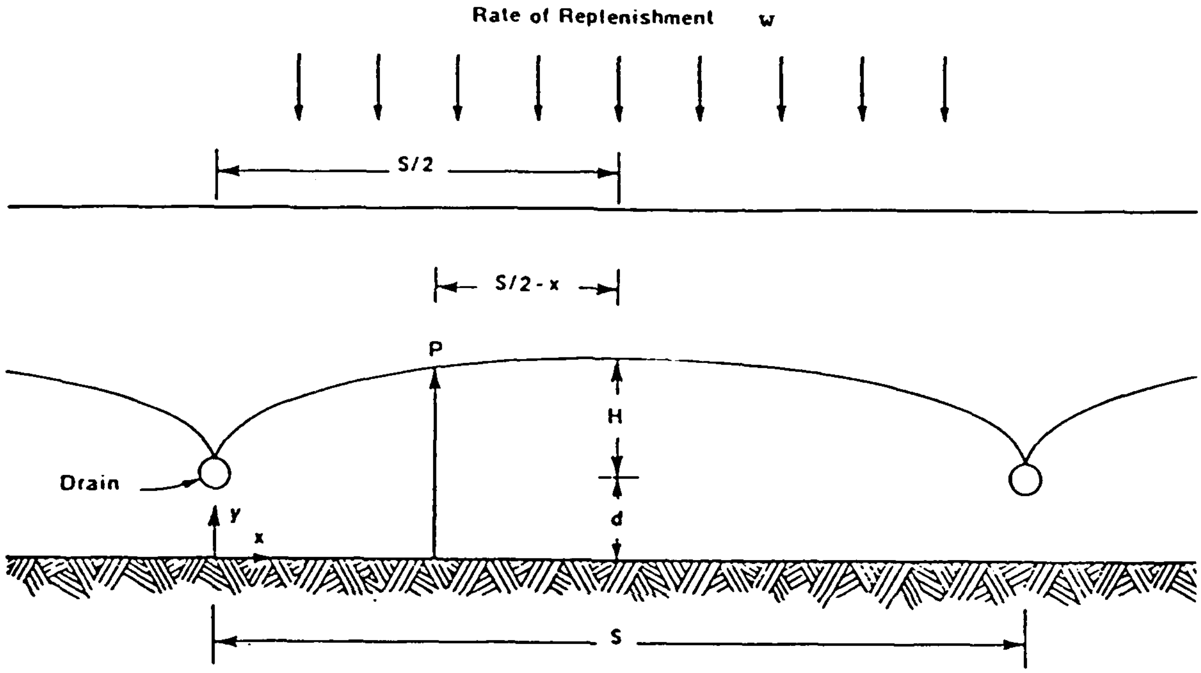

FIGURE 8: Water Table in Steady-State Equilibrium with the Rate of Replenishment (Marino and Luthin, 1982)

respectively, in which s is the drain spacing, K is the hydraulic conductivity of the soil, w is the uniform rate of recharge, and x and y are Cartesian coordinates. The rate of replenishment or recharge can be estimated as discussed earlier.

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CONJUNCTIVE USE FACILITIES

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STORAGE FACILITIES

Physical facilities are used in water resources projects for two primary purposes, namely 1) to store, convey, treat and distribute water, and 2) for project management, operation and maintenance. For the first purpose, structures such as dams, pipelines and canals, well-fields, treatment plants and blending reservoirs, groundwater injection wells, surface spreading basins and supply distribution networks are used to improve the utilization of water resources (increased yield), to maintain an acceptable level of water supply quality. To achieve the second purpose, facilities such as management offices, maintenance yards and operations control centers are used. These "secondary" facilities are an integral part of any water supply project.

There are three types of water storage, namely underground storage, surface storage, and above-ground storage. The facilities needed to store water on and above ground are different from the facilities required to store water underground. Each type of storage has advantages and disadvantages, and water resources planners should take these into account when evaluating alternatives.

a. Underground storage: a major advantage of underground storage of water is that aquifers provide a natural storage facility. Moreover, the storage volume in many aquifers is much larger than that normally contained in on- or above-surface storage. Thus, nature provides a large depository of water -- or available storage space -- that can be exploited at relatively low cost; (man-made facilities are usually required to feed water to and from the aquifer). Another important advantage of understanding storage is that water moving through aquifers tends to undergo a purification process that can result in a high quality water supply. Evaporation losses are zero from aquifers.

The advantages of underground storage of water are clearly very significant. In fact, aquifers are an important source of water in many areas of the country. In some cases, over-exploitation of groundwater has led -- or is leading -- to serious problems, such as dramatically increased pumping lifts, land subsidence, and deteriorating water quality. Other potential problems associated with storing and exploiting water underground include chemical contamination. This can be a very serious problem because such pollution is difficult to remove and may render the underground water supply useless. Also, some groundwater may percolate so deep as to make recovery uneconomic, or it may simply flow away from the recovery area.

b. Surface storage: Capturing surface runoff in impoundments behind dams is a common way of storing water. The water stored in reservoirs may, because of the variable nature of inflow, fluctuate between the bounding conditions of drought and flood. It is these extreme conditions that can cause shortages and surpluses of water. In many reservoirs, the storage volume is divided up into zones to facilitate management of the stored water in times of flood, "normal" inflows, and drought.

Evaporation can be a significant loss of water from surface storage -- up to 10 feet per year in the southwest. Pollution entering a reservoir is usually easier to "flush out" than for aquifers. Some parts of the country are able to use water which is stored in natural reservoirs -- that is, in lakes. The Great Lakes are, of course, the leading example of this situation.

c. Above-ground storage: Above-surface storage facilities consist of water towers, storage tanks and standpipes. The storage capacity of this type of facility is small compared to reservoirs, and tiny compared to underground storage volume. Often, this form of water storage is used to maintain adequate pressure in water distribution networks.

Many conjunctive use schemes take advantage of the favorable characteristics of both surface and subsurface storage of water. In particular, long-term water availability is enhanced through use of the large storage volume in most aquifers to store surplus surface water that would otherwise not be saved for future use. Also, when surface supplies dwindle in droughts, underground water pumping can be increased to make up the shortfall. Low quality surface water, including wastewater effluent, may be brought up to an acceptable standard after percolation through an aquifer, and aquifers can be used to transport water at little or no cost. Planning, design and construction criteria for storage facilities are well-documented: Linsley & Franzini, 1970; Viessman & Welty; 1985; Green and Eiker, 1983.

TRANSFER FACILITIES

Water is moved from place-to-place in various natural and man-made systems. Stream channels -- provided by nature -- are, of course, very attractive means of transporting water. In situations where it is required to move water in directions not followed by rivers and streams, man-made facilities are provided. The selection of a particular type of man-made conveyance -- pipeline, tunnel or open channel -- depends on a number of factors. These include topography, energy costs, construction costs, environmental considerations and the nature of physical works along the route that must be followed. The water conveyance system is used to move water from storage reservoirs, river intake plants, well-fields and other water sources to treatment plants, recharge areas, irrigation canals, water supply distribution networks, power plants, etc.

Details concerning the design and construction of pipelines and aqueducts, and of the nature of flow in natural channels, is well-documented: Linsley & Franzini, 1979; Henderson, 1966; Chow, 1959; Hsieh, 1979; Jansen, 1979.

In conjunctive use, conveyance facilities may have special uses. The most important of these is the transport of water that is in excess of storage capacity in one area to other areas that have surplus capacity, such as an aquifer. Transport of water from one storage facility to another is unique to conjunctive use.

In projects that <u>artificially recharge</u> water to aquifers the ideal transfer facility may be permeable beds of rivers or abandoned gravel and sand excavations. However, such ready-made features are often not available, and surface spreading basins or injection well-fields have to be constructed. Table 1 presents a summary of the advantages and disadvantages of artificial recharge with spreading basins or injection wells.

Basins require primary or, at most, secondary treatment of applied water. The tendency of basins to clog is, of course, primarily a function of applied water quantity, quality and soil type. Algae can be a problem in basins if the incoming water is high in nutrients. Injected water should be of potable quality, low in nutrients with prechlorination for stabilization prior to injection. Recharge water must be compatible with both native groundwater and the minerals of the aquifer strata. Lack of attention to this requirement can create situations that quickly void all benefits of recharge (Joseph, 1981). The major factor in the selection of wells vs basins is the hydrogeology of the area. Basins are usually not suitable for recharging confined aquifers; where a stratum of low permeability separates recharge water from the aquifer to be recharged then subsurface injection is more suitable. Other things being equal, recharge basins are generally favored in locations with enough inexpensive, undeveloped land. In some circumstances, a combination well - basin system can be appropriate (Asano, Ed., 1985).

It is convenient to categorize the areas of the basin according to their suitability for injection. Five categories of suitability have been suggested (Camp, Dresser & McKee, 1983):

1) Highly suitable for injection
2) Suitable for injection
3) Potentially suitable for injection
4) Unsuitable for injection
5) Suitability for injection unknown

In general, criteria that might be used to distinguish the different categories are (1) cumulative aquifer zone thickness and composition, (2) hydraulic properties of the aquifer zones, (3) well specific capacity, (4) well yield, (5) proximity to basin boundaries, (6) depth to groundwater and available storage capacity, and (7) overall quantity and quality of the data available.

RECHARGE BASINS vs INJECTION WELLS

Basins

PRO

1. Technology is well-developed
2. O&M costs are better defined
3. Less severe water quality constraint
4. Possible recovery with shallow wells

CON

1. High land requirement
2. Tendency to clog
3. Losses due to evaporation and absorption
4. Vector problems
5. Possible flooding of adjacent sand & gravel operations
6. Possible formation of perched aquifer
7. Possible contamination from adjacent landfills
8. Vista problems

Wells

PRO

1. Minimal water loss
2. Little new land acquisition
3. Easier to construct in urban areas
4. Minimal cleaning cycle time
5. Easier to fit into a tight management schedule

CON

1. Injection water must be high quality
2. Stabilization required to prevent precipitation and biological degradation
3. Air entrainment can be a problem

TABLE 1: Merits of Recharge Basins and Injection Wells

TREATMENT FACILITIES

Full information on water and wastewater treatment is to be found in a number of excellent texts: Tchobanoglous & Schroeder, 1985; Peavy, Rowe & Tchobanoglous, 1985. Three points are pertinent:

1) Conjunctive use does NOT usually mean the development of very advanced forms of water and wastewater treatment; (Water Research Capsule Report, OWRT, 1978).

2) The conjunctive use of waters of different qualities MAY require the water to undergo additional treatment processes than would otherwise be necessary. This is particularly true for water recharged into granular materials through injection wells (well-aquifer interface clogging and compatibility with native groundwater, as discussed earlier).

3) In some cases, conjunctive use can reduce, or remove, the need for new treatment capacity: chemically compatible water recharged through surface spreading basins -- water which does not have to be of the same high quality as water injected through wells -- can undergo a rapid and effective improvement in quality as it percolates through the soil.

CHINO BASIN, CALIFORNIA

Consultants to the California Department of Water Resources (DWR) and the Metropolitan Water District of Southern California (MWD) have studied the feasibility of increasing the long-term yield of the California State Water Project by implementing a groundwater augmentation program in the Upper Santa Ana River watershed, located in San Bernardino County, and parts of Riverside and Los Angeles Counties (Camp, Dresser & McKee Inc., 1983). Under the proposed storage program, excess State Water Project water would be delivered to the Chino Groundwater Basin (Figure 9) and stored underground or exchanged for water in storage during periods when there are abundant supplies in the State Water Project System.

The Chino Groundwater Basin (Figure 10), which covers an area of approximately 220 square miles, is a flat alluvial valley with an estimated underground storage volume of 13 million acre-feet. Three projects have been proposed and these are expected to require 1.7 million acre-feet of storage space and increase the firm yield of the State Water Project (SWP) by 184,000 acre-feet per year.

In the first project, excess SWP water in "wet" years would be delivered through an enlarged East Branch of the California Aqueduct to MWD's Foothill Feeder. A new pipeline would connect the Foothill Feeder with another of MWD's transmission pipelines, the Upper Feeder. A 600 feet fall in elevation would justify a new 20 MW hydropower facility at the end of the proposed line.

Recommended recharge facilities include four existing, but improved, spreading basins and 11 new dual-purpose injection/extraction wells. The basins would recharge about 25,000 acre-feet in "wet" years. This figure is based on infiltration rates between 2 to 3 feet/day, and a 50 percent use factor (7 days wet and 7 days dry). Necessary improvements to the basins include

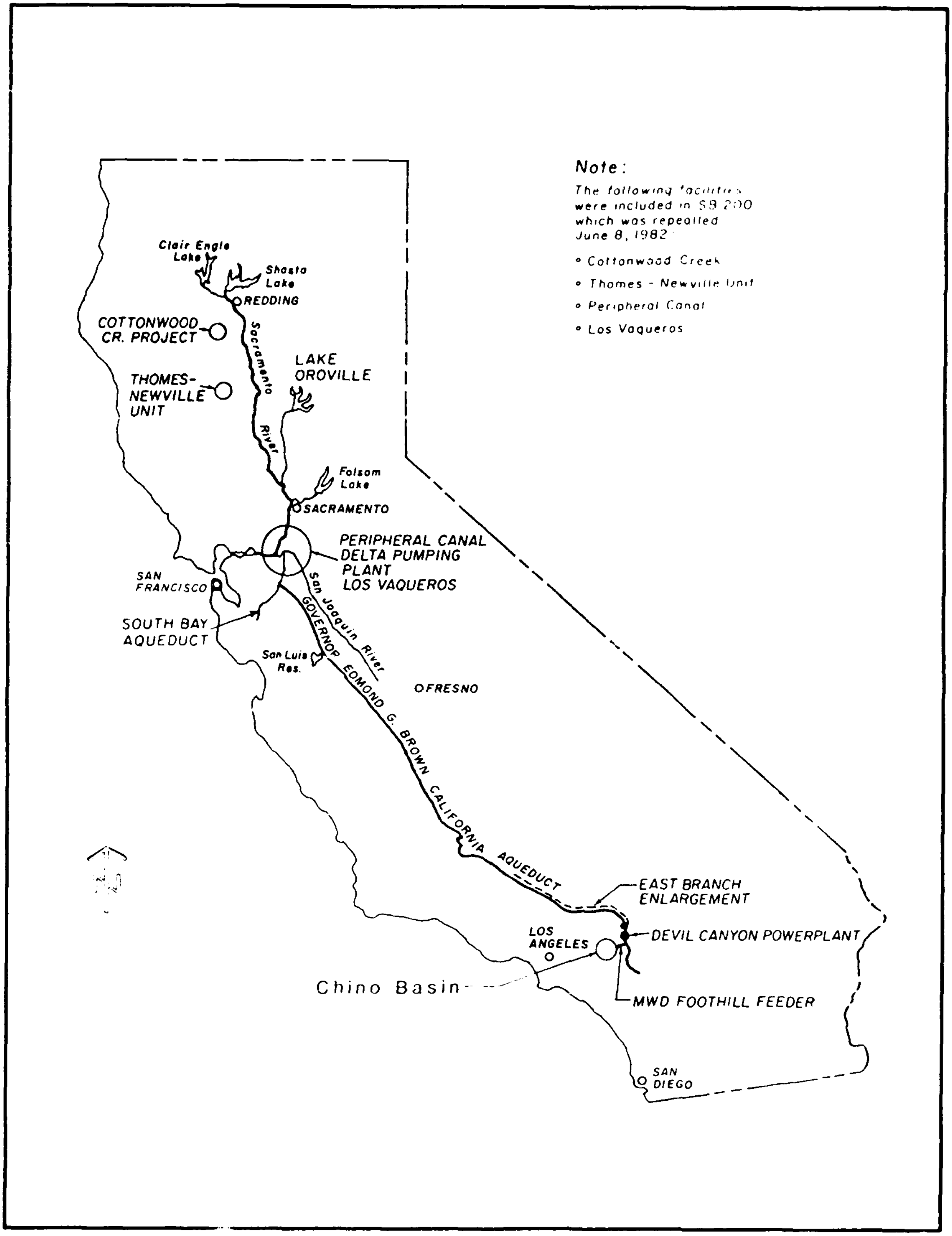

FIGURE 9: California State Water Project
Project Facilities

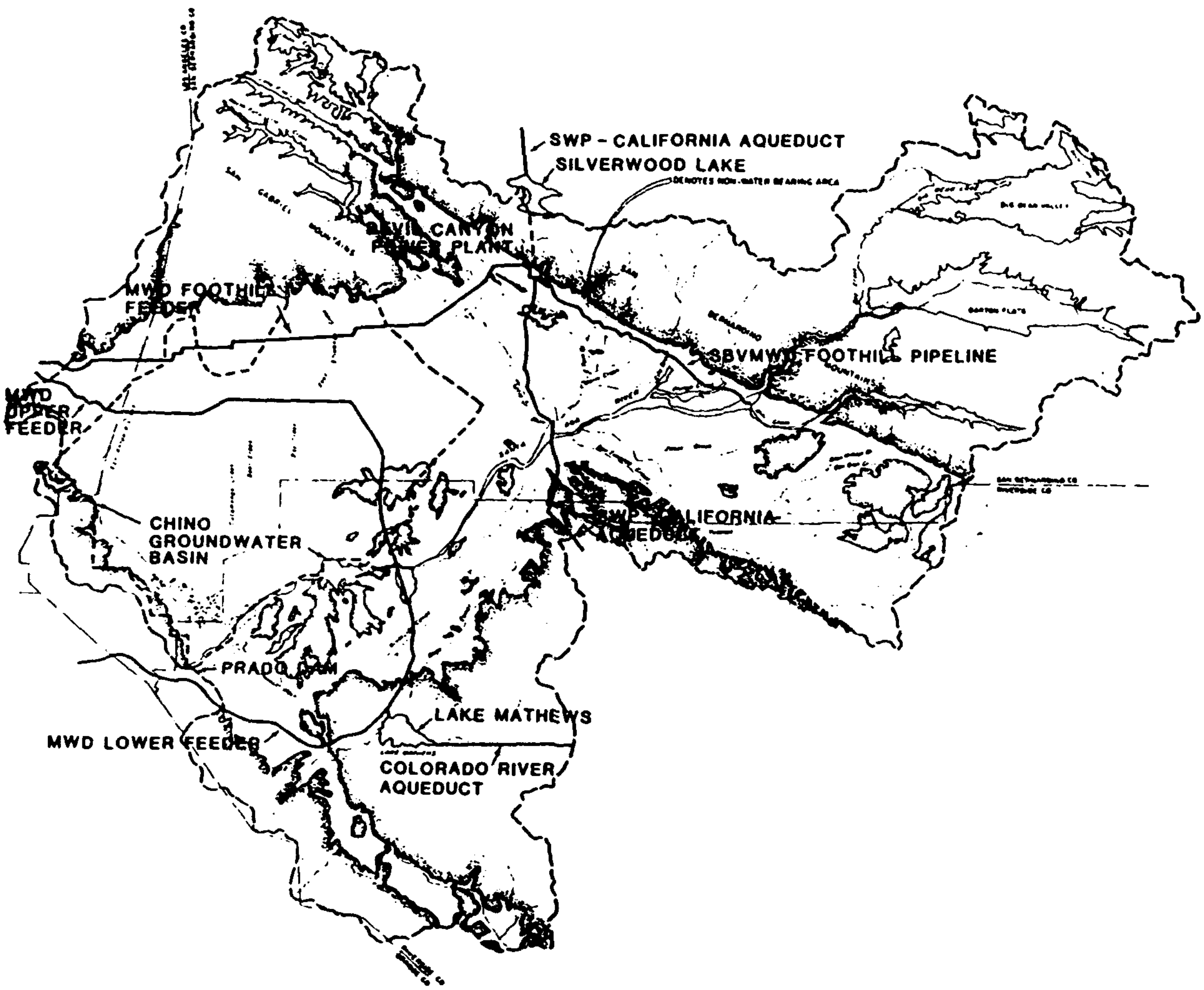

FIGURE 10: Chino Groundwater Basin

the removal of fine sediments currently trapped in the top few inches. A new treatment plant will filter and disinfect water intended for recharge through the dual purpose wells, which will have the capacity to inject up to 25,000 AF/yr. The injection wells will also be used to extract water during periods of SWP supply shortages.

Down gradient from the spreading basins and injection wells an east-west line of 12 extraction wells is planned adjacent to the MWD Upper Feeder. These wells will pump water directly into the Upper Feeder.

The second proposed project provides indirect storage by exchanging water between the MWD and water agencies in the West Chino Basin (cities of Chino, Ontario, Upland, together with the Monte Vista and Chino Basin Municipal Water Districts). This project would store up to 25,200 AF/yr in "wet" years. Essentially, this project uses surplus capacity in the MWD treatment system to reduce pumping from the groundwater basin.

The facilities required include a new 48 inch diameter pipeline, approximately six miles long, between the MWD's Weymouth Filtration plant and the western boundary of the Chino Basin Municipal Water District. For the exchange to be feasible, the cities would also have to build a proposed filtration plant and a new 36 inch (to 24 inch) transmission main from this plant to the service area. Also, new connector lines and other facilities would be needed to take water from the Weymouth Plant line. Fourteen new 3,000 gpm extraction wells -- in addition to those in the first project -- would be constructed in the Chino Basin to recover the stored water made available by the exchange. In dry times, these wells will pull water from the basin to supply the cities and for export to the MWD distribution system. It is estimated that the west basin cities could save up to $12 million in reduced capital expenditures and reduced groundwater pumping costs.

The third project recommended by the study group also involves a water exchange. Four water agencies to the north of the City of Ontario which have pumping rights in both the Chino and Cucamonga Basins would exchange "their" water stored in the Chino basin for excess SWP water delivered to surface spreading basins in the Cucamonga Basin. It is thought that the project could recharge up to 6,100 AF/yr of excess SWP water in wet years. Three new extraction wells would be built and a proposed transmission line would be enlarged from 30 to 36 inches diameter. Over a project life of 50 years, it is estimated that the local agencies could save up to $13 million in reduced energy and capital improvement costs. Four new wells would be constructed in the Chino Basin to recover water made available under the third proposal. As in the first proposal, these wells would be located along the Upper Feeder and water pumped directly into the line.

The capital cost of the recommended storage program (i.e., of the 3 projects) is $89 million (1982 dollars). Thirty-nine percent of this cost is for enlargement of the East Branch of the California Aqueduct; 27 percent is for wells; 17 percent is for new pipelines and 9 percent for water treatment and power recovery facilities. Improvements to existing spreading basins and new connections (turnouts) between the proposed facilities and the MWD system account for just 5 and 3 percent of the estimated cost. Land costs -- even in the Los Angeles metropolitan area -- are a negligible capital cost component. O&M costs will vary considerably from one year to another, but are expected to average $2.8 million per year over a 50-year period. The unit cost of additional firm yield is estimated to be $92/AF, excluding the cost of delivery to the Chino Basin.

CITY OF TACOMA, WASHINGTON

Tacoma's principal water source, the Green River, seasonally experiences excessive turbidity due to suspended colloidal clay (Roller & Moline, 1978). Normally, water abstracted from the Green needs no clarification, sedimentation or filtration. However, for a period of 60 - 65 days in the late winter or early spring flow in the river becomes increasingly turbid. When this occurs Tacoma augments the river water supply with groundwater The innovative system is designed to blend high quality groundwater with turbid river water, thereby reducing the turbidity of the city supply water to an acceptable level.

The conjunctive use system comprises four distinct sets of facilities -- the first set being river abstraction and spill chamber works (Figures 11 and 12), the second consisting of groundwater pumping wells, the third set associated with the water quality sensing function, and the fourth to the integrated communications network used to operate the system. Six high capacity (8,333 gpm) pumps are installed in abstraction wells in the North Fork well-field. Water is conveyed from the well-field by a 7-mile long pipeline to a 10-million gallon above-ground storage tank, which is kept full.

The water quality control station contains six water blending valves which are controlled automatically, with adjustments being made according to the turbidity level as sensed by turbidimeters located at the river intake and also at a point downstream on the main supply tunnel to Tacoma. As flow from the tank is increased, a "hydraulic block" reduces the flow from the river intake (the water surface elevation -- 958 ft. -- is higher than the spill chamber, which is at 900 feet above datum; apply Bernoulli's equation between the two water surfaces and a point downstream!). When all six blending valves are open, flow from the river is completely cut-off. As the

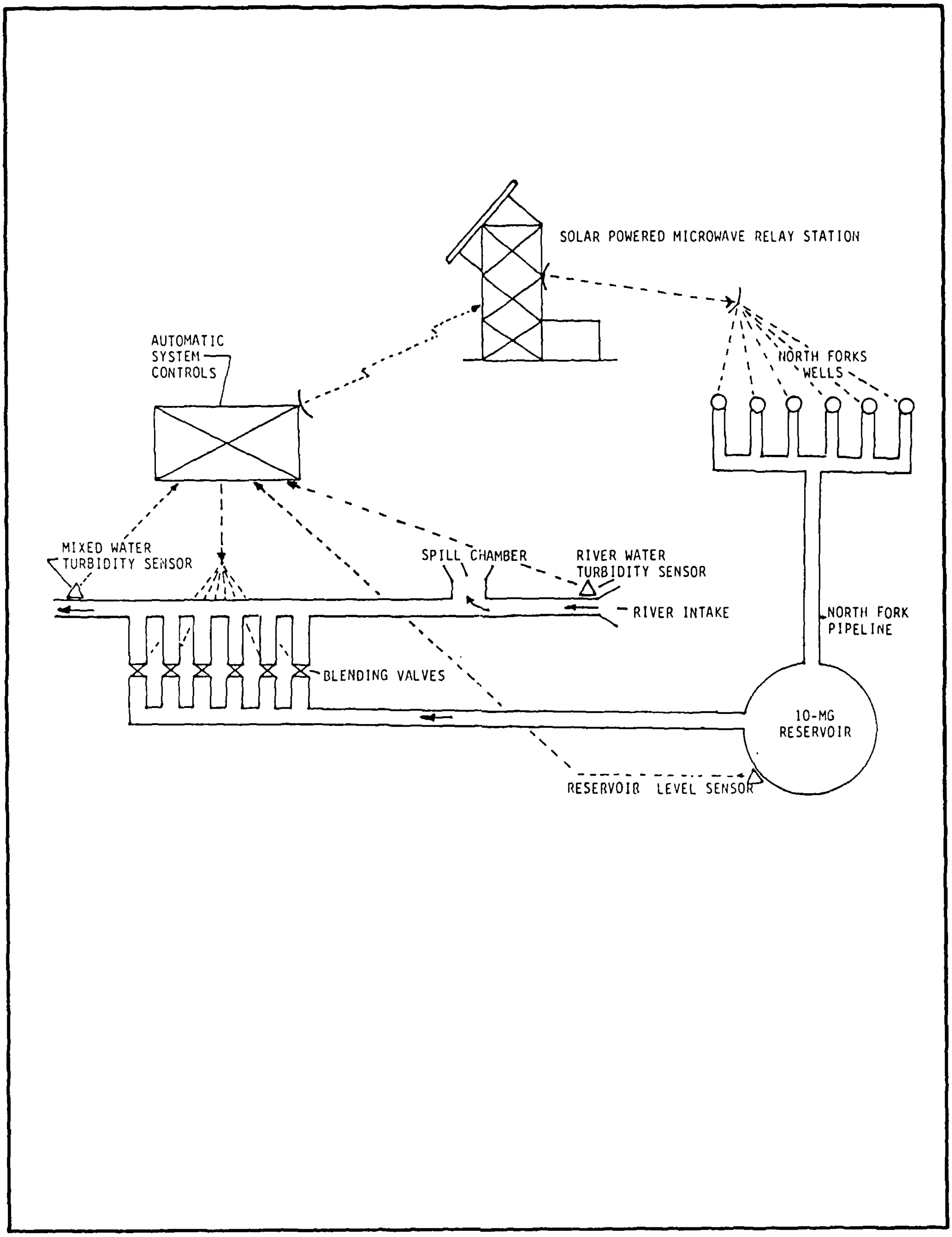

FIGURE 11: Water Supply System, Tacoma, Washington (Rol?er, 1978)

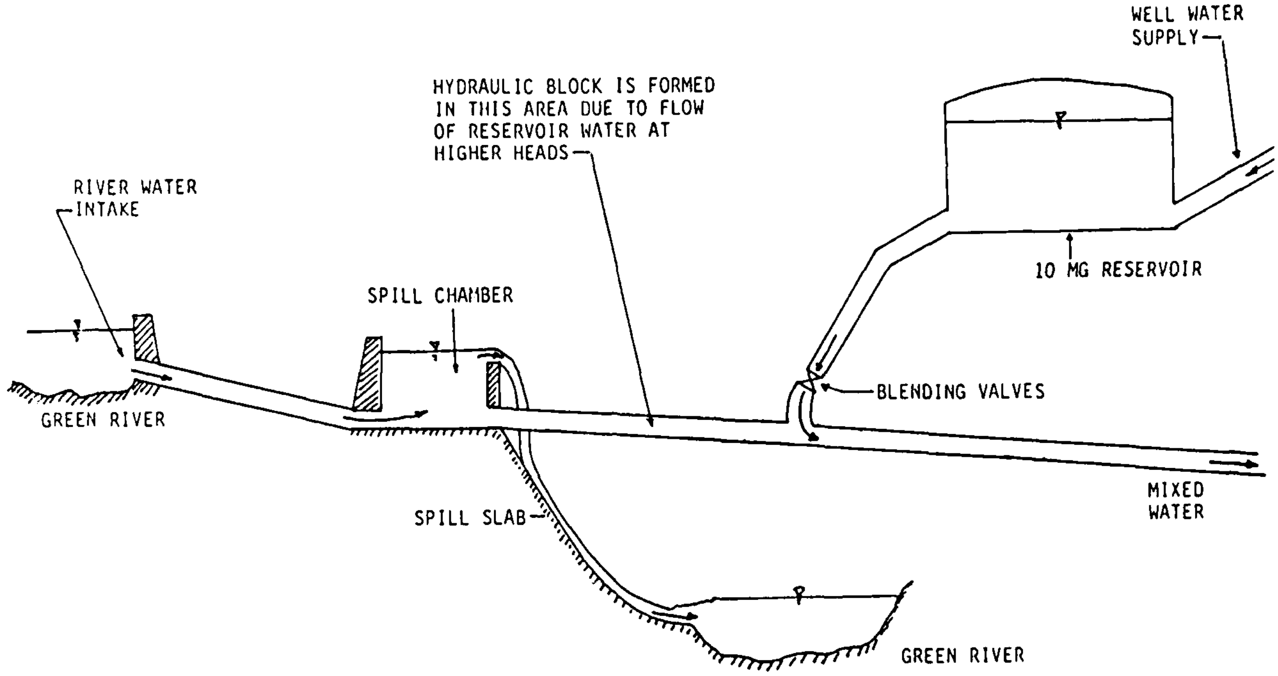

FIGURE 12: Well water Supply Control System
(Roller, 1978)

blending valves are opened, the water level in the groundwater storage tank drops.

A sensor registers the falling level and signals a component of the third set of facilities, namely the automatic system controls. A falling water level in the tank activates one or more of the groundwater pumps. The other major system control function is to monitor the readings of the turbidity sensors and send appropriate signals to the blending valve actuators. Microwave communications between the system control building, pump actuators, blending valve actuators and the turbidity and reservoir level sensors are powered by solar energy. The Tacoma water supply system is an example of conjunctive use of surface and groundwater (both sources are hydraulically connected, but clearly can have differing qualities). Note that there is no artificial recharge involved, and that blending for optimal water quality dictates the "degree" of conjunctive use at any time.

PHOENIX METROPOLITAN AREA, ARIZONA

One potential application of conjunctive use planning is the coordinated management of the water resources available to the Greater Phoenix area. Currently, water is supplied to an extensive canal system (Figure 13) from a network of surface reservoirs operated by The Salt River Project (SRP) (Figure 14), and numerous wells operated by SRP, area cities and others. By early 1986, the area will receive water from the Colorado River via the Central Arizona Project (CAP). This "imported" water supply, dreamed of for many decades, is about to become a reality.

As the far-reaching Groundwater Management Act of 1980 begins to have an impact on well pumping, Phoenix area cities are currently (summer/fall 1985) focusing on artificial recharge of the groundwater aquifer, which has been seriously over-exploited. The use of reclaimed wastewater for urban irrigation (parks, golf courses, etc.) is being studied, as is the impact of enlargement of the biggest SRP dam (Roosevelt).

Surface water, groundwater, imported water, artificial recharge, wastewater reclamation and radical new groundwater legislation all tied together to serve a rapidly growing semi-arid urban community ... it is not difficult to realize that water use efficiency will be maximized if the sources are managed as a "total water resource".

The primary purpose of the seven SRP dams is to supply water for irrigated agriculture. However, rapid urbanization of the Phoenix area has diverted an increasing amount of this water for M & I use. The surface water supply is augmented by some 360 wells, some of which discharge directly into the distribution canals. Most of the Phoenix area cities divert water out of the

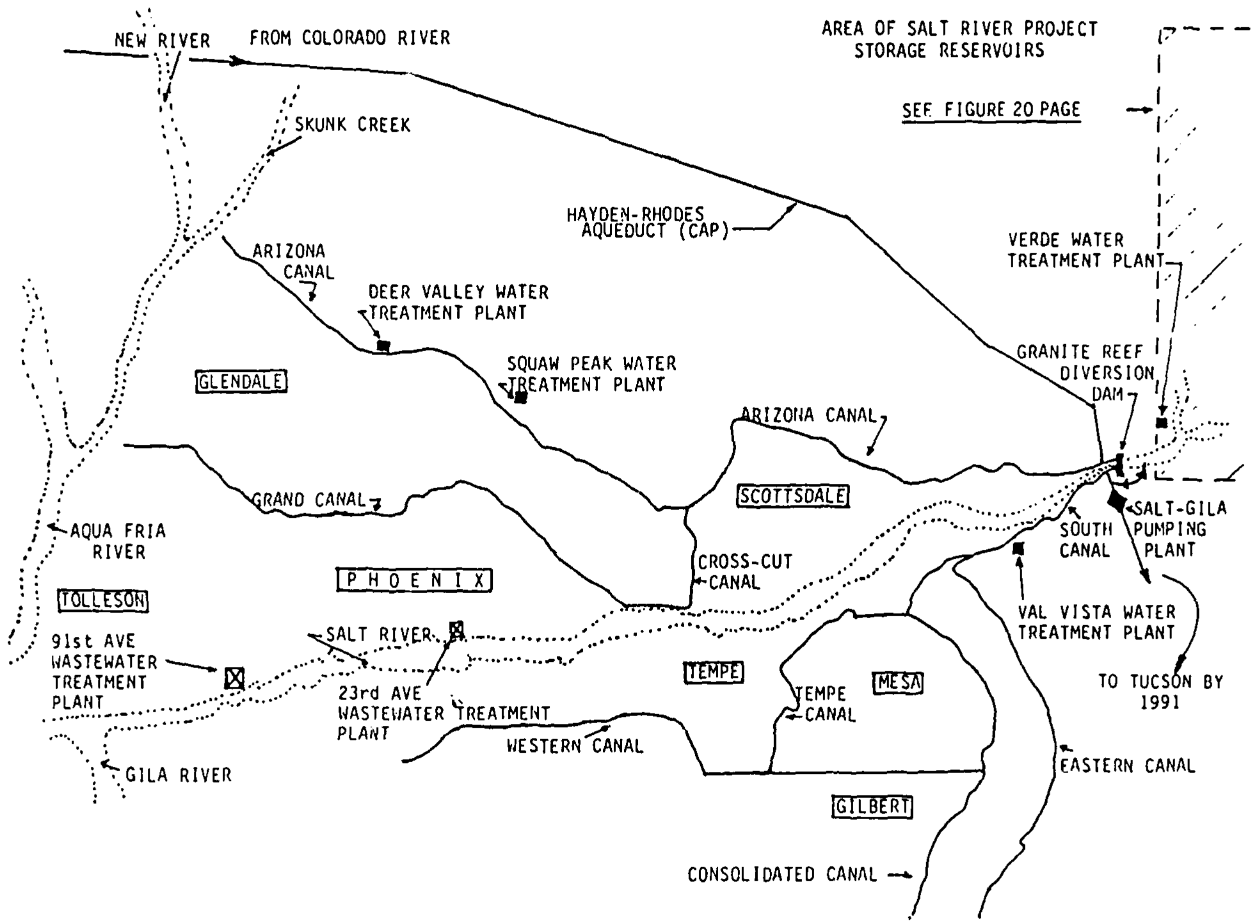

FIGURE 13: Current Extensive Canal System, Phoenix, Arizona

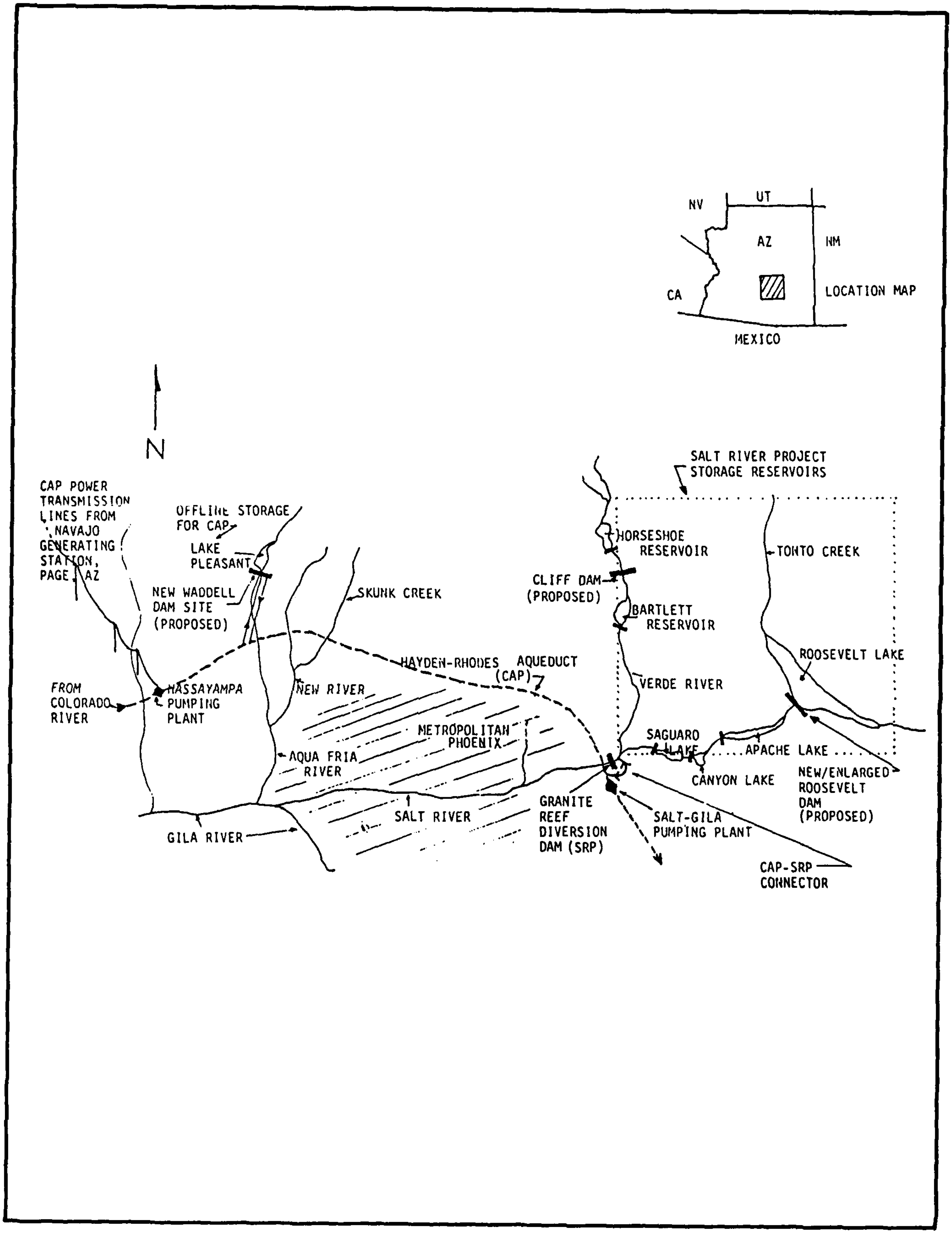

FIGURE 14: Network of Reservoirs Operated by the Salt River Project, Phoenix, Arizona

SRP canals directly into treatment plants (Figure 13). New treatment plants are currently under construction near the Hayden-Rhodes Aqueduct of the CAP to treat the low quality Colorado River water (e.g., hardness = 320 - 340 mg/l).

Most of the wastewater effluent produced in area cities is sent to a 120 mgd regional treatment plant to the southwest of Phoenix. This plant is currently committed to supplying treated effluent for cooling purposes at the Palo Verde Nuclear Power Plant, which will begin commercial operations towards the end of 1985 and will have the dubious distinction of being the largest nuclear plant in the country when all three reactors are on-line in 1987. Effluent in excess of the needs of the power plant is discharged to the Gila River and is used by downstream agricultural interests. Some of the area cities are interested in "intercepting" sewer flow before it leaves the city limits, diverting it into small (e.g., 4 mgd) reclamation plants constructed alongside trunk sewers, and using it for urban greenbelt irrigation. This will enable the City of Scottsdale, for example, to release well water being used for this purpose for potable water needs (Hinks & Saldamando, 1985).

Most of the facilities required to conjunctively manage the various water resources are either constructed, under construction, or planned. These facilities include the CAP aqueduct, CAP-SRP intertie at Granite Reef Dam, CAP water treatment plants, small wastewater reclamation plants, and recharge injection wells. The real challenge is ahead: how to overcome institutional inertia and establish an integrated management system for this complex network.

ELGIN, ILLINOIS

The centerpiece of Elgin's water system improvement plan is the new 16 mgd Riverside Water Softening Plant (Civil Engineering, 1984). The plant is designed to treat 100% river water, 100% deep well water or any combination of both; the amounts are balanced according to the availability and quality of each source.

Figure 15 shows a schematic layout of the plant. Plans call for an expansion of capacity to 32 mgd, which will necessitate duplicating the components shown. Water from the Fox River is pumped to a pre-sedimentation basin where alum and potassium permanganate are added. Well water is pumped through a separate line to an aeration basin in order to remove hydrogen sulphide. Both waters are then softened, followed by the conventional processes of sedimentation, coagulation, chlorination and filtration. The treated water is stored in two clear wells below the filters, and in an above-ground steel tank of 1 mgd capacity before being pumped into the distribution system.

The flexibility allows plant operators to respond to changes in raw water quality and quantity. For example, the use of well water would increase during low flows in the river, or if there was any sudden contamination upstream. Also, the Water Department can adjust the two flows to minimize the impact of an increase in the cost of chemicals, or to take advantage of lower costs, etc.

Having used Fox River water for many years, Elgin turned to groundwater in the 1920's because of pollution caused by increased industrial activity upstream. In the 50's, with an annual overdraft averaging around 13 - 14 feet (4 - 4.3 m) per year, the City needed to exploit the river again in order to reduce the overdraft and meet increasing needs in a growing community.

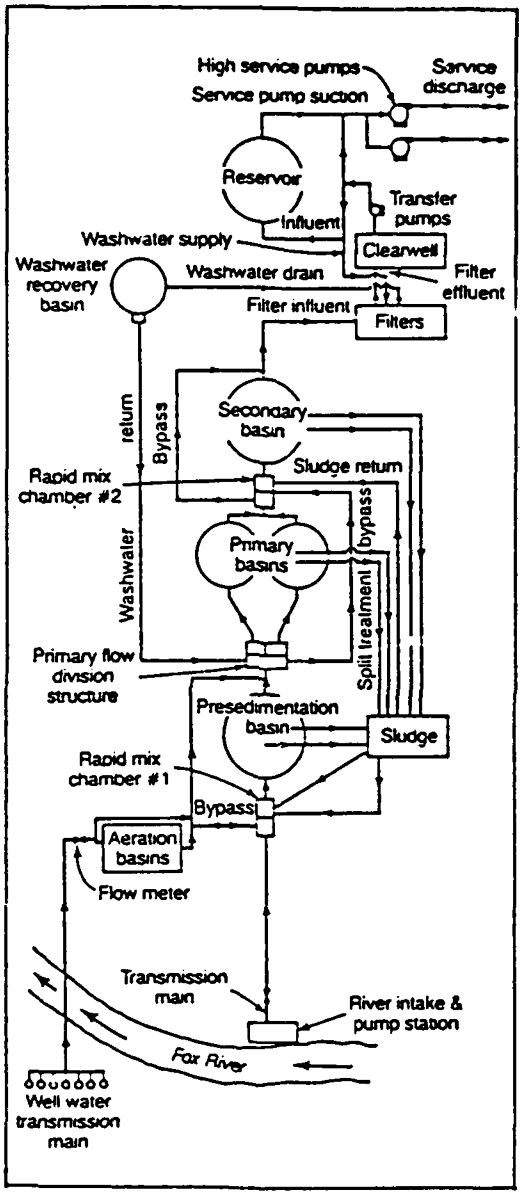

FIGURE 15: Riverside Water Softening Plant, Elgin, Illinois

WATER FACTORY 21, CALIFORNIA

Water Factory 21 is an advanced wastewater treatment facility capable of producing a high quality effluent for injection into a domestic supply groundwater aquifer (Water Research Capsule Report, OWRT, 1978). Municipal wastewater received from the Orange County Sanitation District is subjected to lime clarification, ammonia stripping, recarbonation, chlorination, filtration, activated carbon absorption and post-chlorination. Approximately one-third of the effluent is then demineralized by reverse osmosis (Figure 16).

Reclaimed effluent, desalted reclaimed effluent and water from deep wells is blended and passed through an injection pump station to 23 multi-point wells that inject up to 250 gpm into each of four separate aquifers. Between the line of injection wells and the Pacific Ocean is a line of extraction wells designed to prevent seawater intrusion by drawing injected water towards them. Recharged effluent also moves inland and is eventually pumped out to begin the use-treatment-injection cycle once again.

Water Factory 21 is an example of conjunctive use that will undoubtedly become more common in the future. Reclaimed effluent, blended to an appropriate extent with groundwater, is recharged to the aquifer in order to enhance supplies and help minimize the effects of saltwater intrusion.

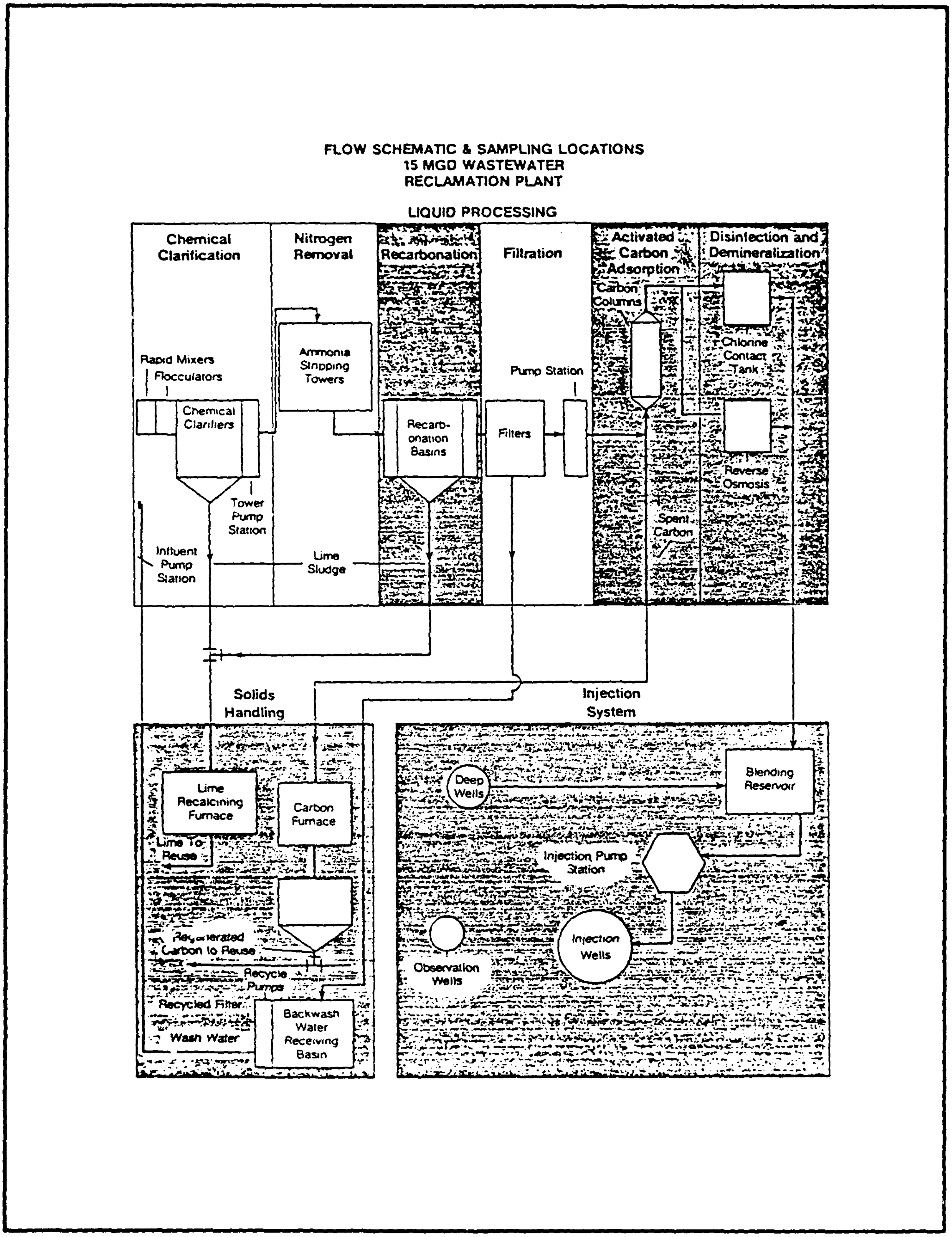

FIGURE 16: Advanced Waste Water Treatment Facilities, Water Factory 21.

STERLING, COLORADO

Effluent is treated and returned to the City of Sterling, Colorado, by pumping the water upstream over a hill and allowing it to slowly return by percolating through an aquifer (Civil Engineering, 1983). By doing this, the city is able to substantially augment its supplies by retaining water that would otherwise be lost downstream to Nebraska (Figure 17).

During the six-month irrigation season, effluent is discharged directly from the city's treatment plant aeration lagoons to the South Platte river. During the remaining six months the effluent is pumped one mile to a 30-acre natural storage/recharge pond. It infiltrates the sandy strata to the unconfined aquifer and percolates back towards the treatment plant and river. Percolation time is approximately five months, so the effluent reaches the river at the next peak demand irrigation season. The quality of the percolating water exceeds EPA discharge standards by the time it reaches the river.

This simple, inexpensive project simultaneously meets water quality and water conservation goals. Moreover, it has enough reserve capacity to more than double the volume of effluent (280 acre-feet in 1982) percolating through the aquifer by modifying the pumping arrangement.

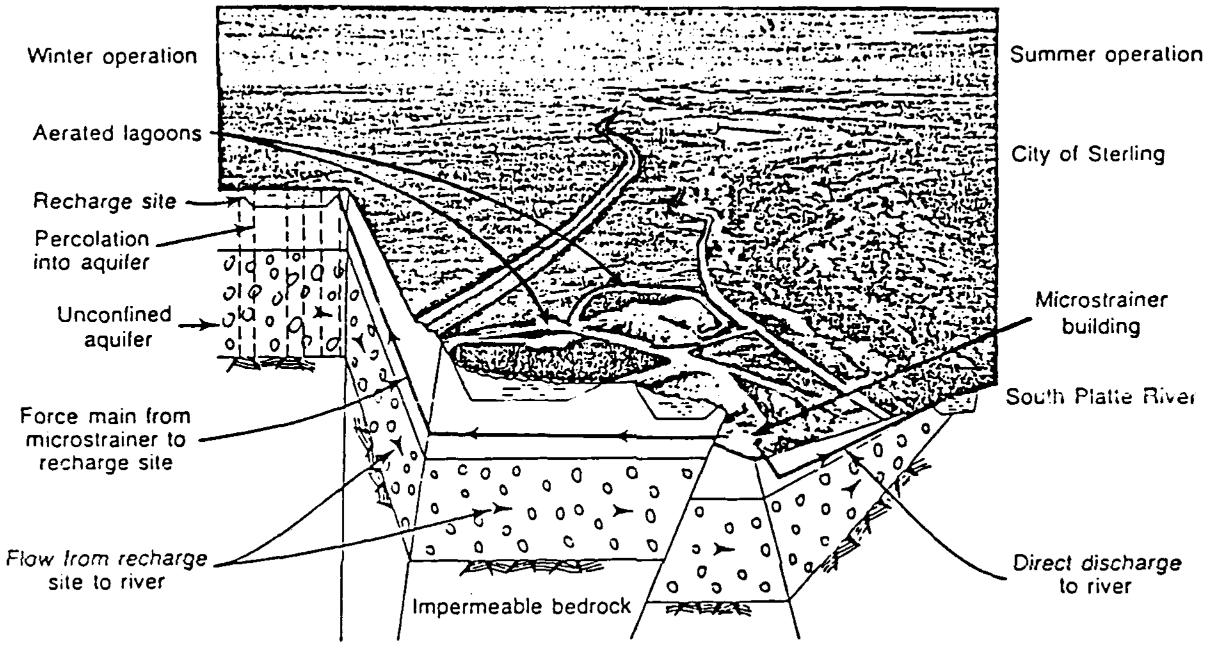

FIGURE 17: Recharge Path, Sterling, Colorado Wastewater Treatment Plant

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A REVIEW OF WATER LAW

Water is not treated like any other resource. The states reserve the power and prerogative to establish the institutions for allocating all the waters within their boundaries not encumbered by federal law or interstate compact. The states grant water use rights based on either a common law doctrine that calls for all users to cut back in time of shortage, or on a system in which the earliest users have the most senior rights (National Water Commission, 1973; Trelease, 1979; Cox, 1982; Frederick, 1986).

The earliest state laws controlling surface waters were based on the common law doctrine of riparian rights, which grants the owner of land adjacent to a water body the right to use the water. Riparian rights are inseparable from the land and are further constrained to uses that are "reasonable" and which do not unduly inconvenience other riparian owners. The basic riparian doctrine does not include a specific priority of use, so all riparian owners usually share in curtailing use in times of shortage. The riparian doctrine still underlies the water codes of almost all the relatively water-abundant eastern states (Figure 18).

State laws guiding the allocation and use of water have evolved over time in response to new conditions, and numerous modifications to the basic riparian doctrine are commonplace. For example, there are different interpretations of what constitutes "reasonable use": in those cases where there are competing uses that in total demand more water than the stream can normally supply, then a court might decree an apportionment between the users. Where the uses are completely incompatible, the court might prefer one use over another. In such cases a court may give an advantage to established uses over proposed new uses, but this is not always the case and, in general, reasonable use conflicts are decided on an individual case basis. It is

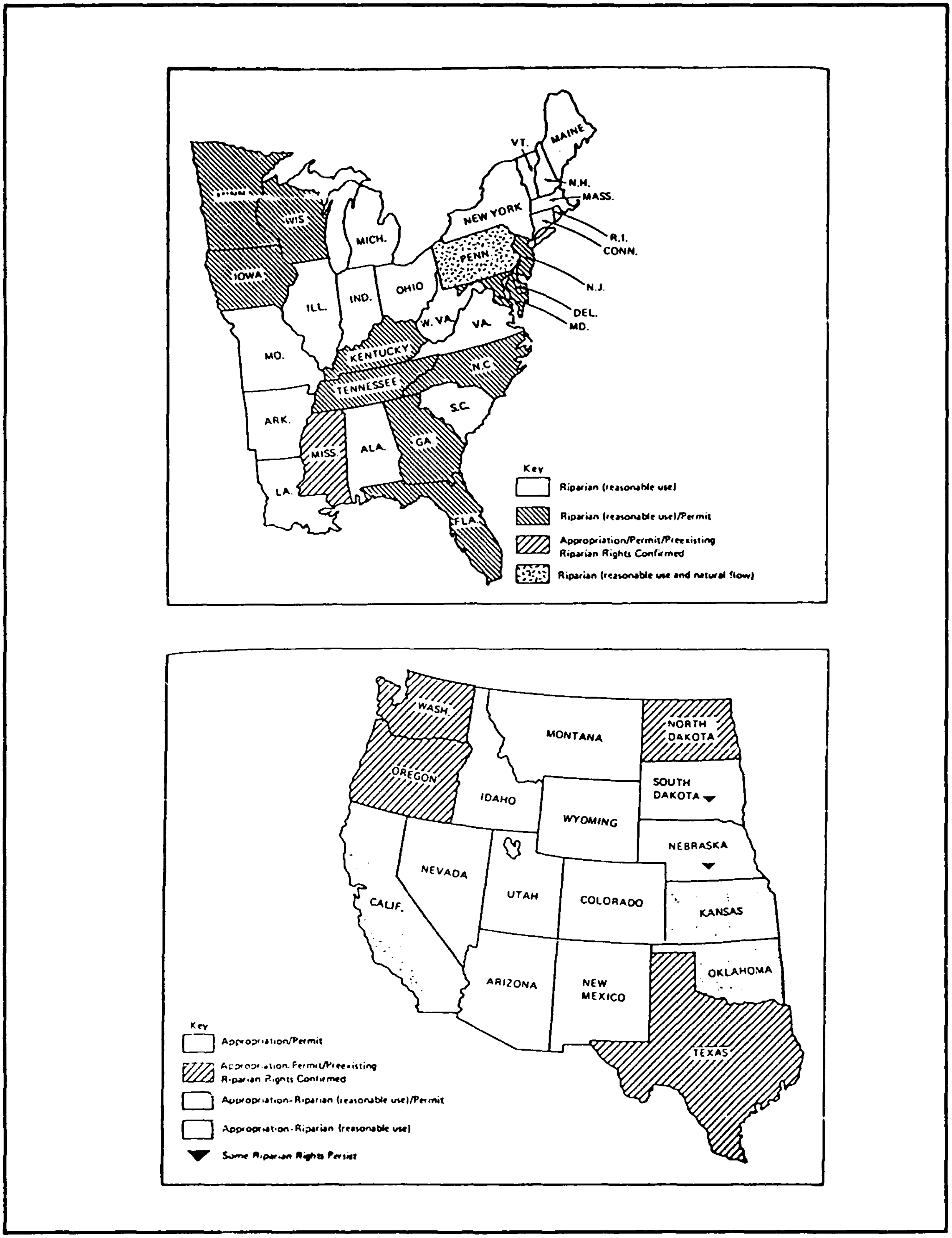

FIGURE 18: Surface Water Rights in the United States

becoming increasingly common for states to require that permits be obtained before riparian rights may be exercised. Such permits often try to ensure that existing water users are not affected by a new user tapping the same source, to maintain sufficient flow for instream needs, and to ensure that water quality is not impaired (Viessman & Welty, 1985). Permits may also impose restrictions on 1) the quantities of water that can be withdrawn, 2) where, and 3) over what period of time, withdrawals can be made. During times of limited supply, users are required to reduce their withdrawals -- although under modified forms of the riparian doctrine some users may be assigned a higher priority, even to the extent of being able to continue at their normal rate of withdrawal. Finally, the permit may require that any change in use of the water be approved in advance by the water agency.

Some experts claim that numerous modifications to the basic riparian doctrine have created unnecessary uncertainty because of the inevitable inconsistencies, redundancies, and omissions inherent in water law that evolves over many years in response to changing conditions (Sherk, 1983).

The riparian system has not been adopted in the arid west of the country where streams are less numerous and their flows smaller and less reliable. Water as a commodity was first a requisite and then a necessity for settlement in much of the west. The early enterprises of mining and irrigated agriculture made the concept of riparian rights impractical, as large expanses of non-riparian land would have been unusable. By the time people got around to deciding what western water law should be, there was already an established precedent that water could be appropriated from streams and taken to wherever it was needed, regardless of land ownership. Thus, even a modified form of the riparian doctrine was infeasible.

The prior appropriation doctrine that is the basis of water law in the seventeen western states asserts that land ownership is irrelevant to the acquisition of water rights, that water can be used anywhere it is needed, and that priority in time determines seniority in times of water shortage -- "first in time, first in right". A right is obtained by merely using water for a beneficial use, and it can be lost by ceasing to make such use. Beneficial uses are those having an economic value (although some states also classify instream flow uses as beneficial).

As is the case with riparian rights, any number of modifications to the basic appropriation doctrine are commonplace (Figure 18). For example, some states give priority to certain uses over others even though their seniority in time may be lower: twelve western states specify a ranked preference of use that allows preferred uses (municipal and industrial first, often followed by agriculture) to supercede water rights destined for less-preferred uses in times of shortage (Frederick, 1986). Appropriation rights may be sold (although the new owner may have to file for a permit if the nature of water use or place of withdrawal changes), and some states have restrictions on exporting the water out of the basin of origin, or to another state.

Appropriative rights eliminate a major obstacle to water transfers by breaking the link between water and land. However, just as is true with riparian law, a variety of legal provisions have, in many instances, amended the basic appropriative doctrine to an extent that tends to hinder rather than aid conjunctive use planners.

One of the obstacles to implementation of conjunctive use plans concerns the fact that groundwater resources have been viewed in a completely different context to surface water resources. Although the science of hydrology clearly understands

all water on earth to be part of a single (total) water resource, water law has evolved under the premise that surface and groundwater are distinct entities, with groundwater having an aura of mystery:

> "Because the existence, origin, movement, and course of such (ground) waters, and the causes that govern and direct their movements, are so secret, occult, and concealed that an attempt to administer any (comprehensive) set of legal rules in respect to them would be involved in hopeless uncertainty and would, therefore, be practically impossible."
> {quoted in (Sax, 1965)}

Although this view -- stated in a 1904 Texas law suit -- is no longer prevalent, the subsequent enlightenment came so late that unfortunate precedents had been set: namely, that groundwater could not be significantly regulated and, secondly, that groundwater was a separate entity, unrelated to surface water. It is the latter precedent that is potentially one of the biggest obstacles to the implementation of conjunctive use plans.

There are four doctrines applicable to groundwater rights: <u>common law</u>, <u>reasonable use</u>, <u>correlative rights</u>, and <u>appropriation</u> doctrines (Figure 19). Common law (also known as the "absolute ownership" and "overlying use" doctrine) allows an overlying landowner to withdraw water in any amount for any purpose. There is no liability for damage to any other user of the same groundwater system (not a problem when the technology for withdrawing large quantities of water did not exist; however, the technical means does exist today). The common law doctrine may be extended to include reasonable use, which considers that landowners overlying an aquifer have equal rights to the use of the groundwater resources; moreover, non-wasteful use is required. In the correlative rights system, rights are allocated in proportion to the extent of ownership of the overlying land; reasonable use may also be incorporated. Finally, appropriation rights are similar for groundwater as for surface water. A

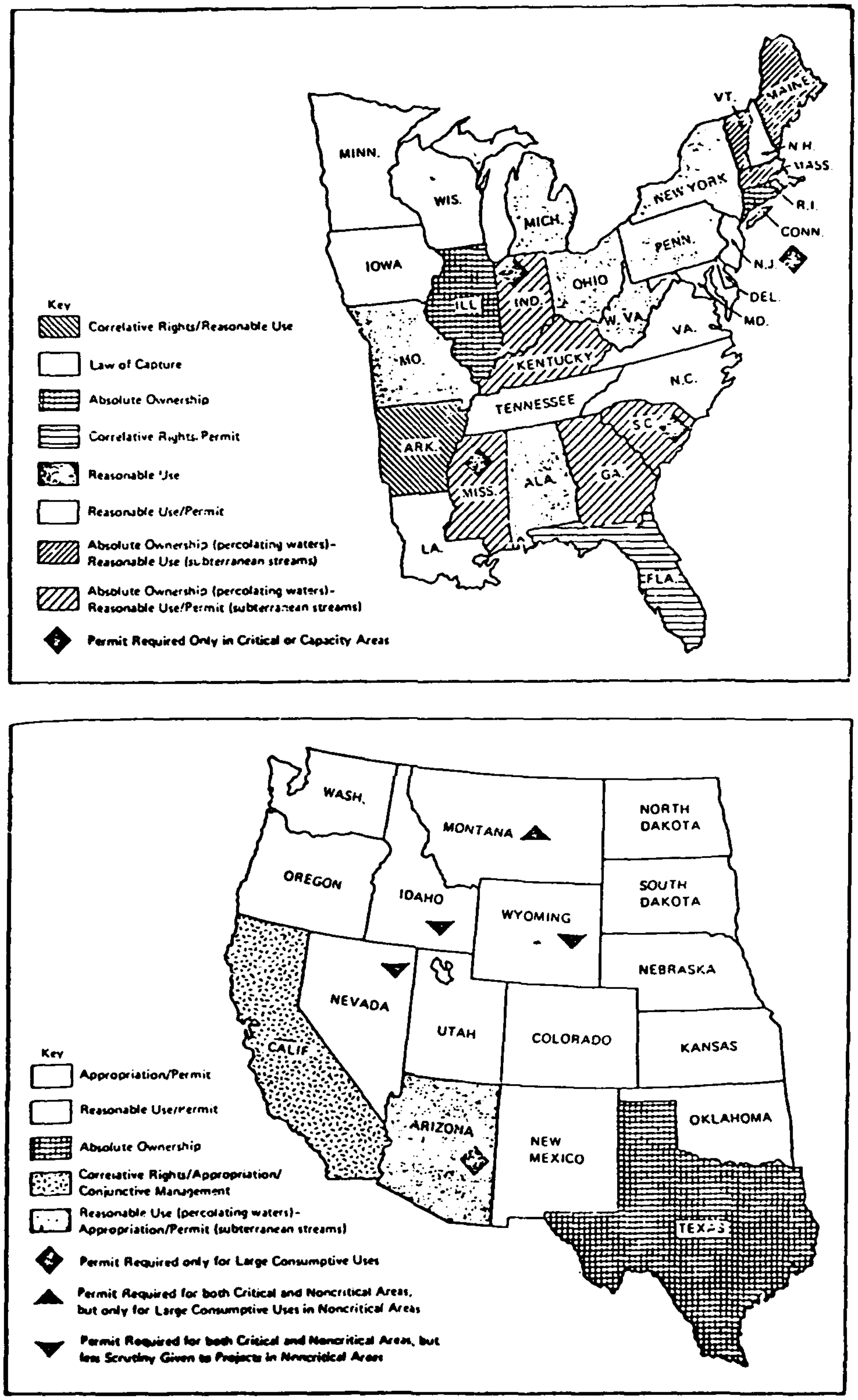

FIGURE 19: Groundwater Rights in the United States

groundwater pumping permit may be required from the appropriate state agency.

Another problem is that the term "groundwater" has no single meaning. Its scope is determined by the language of each state's statute, and there are wide variations in the definition of groundwater (Sax, 1968). Various subdivisions of underground water are recognized by law:

Percolating water
Subterranean water
Artesian water
Tributary water
Rechargeable and non-rechargeable water
Channelized water (water in underground streams)
Mineral water
Geothermal water

Most states reduce these classification of groundwater to just two: percolating and flowing. However, the existence of the other classifications could cause problems for conjunctive use projects.

Most western states follow the appropriation doctrine for both surface and groundwater rights, however, as discussed above, there are numerous variations to this general rule. A good example is Texas, which recognizes <u>both</u> the riparian and appropriation doctrines for surface water in streams. Riparian rights are recognized for early Hispanic and pre-1840 land grants by the Republic of Texas, and there are more extensive riparian rights attached to lands granted by the Republic and state between 1840 and the Appropriation Acts of 1889 and 1895 (Templer, 1983). For the last ninety years, the state has required that prospective water users file an application and receive an appropriation permit. (Initially, this was a routine, informal procedure, subsequently enforced more rigidly). Many

streams have water users exercising both riparian and appropriative rights, with each class of user subject to very different rules.

Texas law divides groundwater into two classes: 1) flowing in well-defined underground streams, and 2) percolating groundwater. The former classification is difficult to determine, and Texas courts presume that all groundwater is percolating unless proven otherwise. Percolating water is the exclusive property of the owner of overlying land, and owners can pump and use the water with very few restrictions. A 1949 statute provided for the establishment of local underground water conservation districts, but few have been formed. Moreover, the conservation districts in existence have had only limited success in addressing the problem of aquifer depletion (Templer, 1983).

PRESENT LEGAL CONSTRAINTS

The review of water law enables us to identify two legal barriers to the implementation of conjunctive use plans: inflexible systems of water rights and the separate legal classifications of surface and groundwater resources. However, other legal uncertainties can be identified. Some of these are related to the evolution of water law, others are more directly related to the consequences of conjunctive use operations.

The fundamental problems related to the evolution of legal policy can be addressed in the following questions:

a. How are established rights of existing streamflow diverters and groundwater pumpers to be modified to facilitate conjunctive use? Water rights are jealously guarded, and few users will willingly relinquish their rights to water. There is an need to adjudicate individual water rights and to develop a strong legal framework for a comprehensive basin-wide management plan (Coe, 1979; Templer, 1980). The riparian rights doctrine, linking as it does water rights to land ownership, is particularly inadequate as an effective system for the management and allocation of regional (e.g., basin-wide) water resources. There are four problems: 1) the difficulty in quantifying existing water use, 2) the lack of protection for existing uses against other existing or proposed new uses, 3) the problem of exemption from statutory requirements for small amounts of water use, (this continues the uncertainty concerning the quantification of total water use in a region), and 4) the problem of water allocation in times of shortage. Some experts argue that it is preferable for states to adopt a specially-crafted form of the appropriation doctrine rather than make numerous adjustments to the basic riparian system (Cox, 1983; Sherk, 1983). Even with appropriative rights, a variety of legal provisions often tend to inhibit the creation of well-defined, transferable property rights in water.

b. <u>What is the potential effect on conjunctive use of the legal partitioning of water moving through the hydrologic cycle</u>? There is no legal recognition of the interrelationships existing within the hydrologic cycle, and different rules of law have been developed concerning the ownership and use of the various classes. This legal division of water into discrete classes could be a significant barrier to the establishment of general rules for conjunctive use operations. Moreover, in some states, changing such well-established legal principles could be very difficult to overcome. It is believed that in Texas, for example, any attempt to extend the appropriation doctrine to groundwater would probably be considered an unconstitutional taking of property (Templer, 1980).

c. <u>How are other water management and operations policies previously established by law to be modified (where necessary) to facilitate conjunctive use</u>? In many states, legislation has amended the basic riparian and appropriation doctrines in order to establish rules concerning such things as low flow requirements in streams, priorities for reservoir operations, the preferential treatment of some beneficial uses, and restrictions on off-site use, such as use outside the basin of "origin" and inter-state transfers of water (Beard, 1983). In some states, substantial funds set aside for statewide projects (e.g., California's State Water Project) are not legally available for local or regional projects -- projects that could be elements of a conjunctive use plan that reduces the need for expansion of an expensive statewide facility (Coe, 1979).

d. <u>What is the impact of riparian and appropriation doctrines on the issue of compensation in inter- and intra-basin water transfers, and what is the effect of such compensation on conjunctive use planning</u>? Diverting ground or surface water, with the intention of using it in a conjunctive use project, could deny other users of their rightful share of the resource. Such action can lead to intense controversy and

litigation, bringing established concepts of ownership into direct conflict with modern legal ideas of government regulation and public ownership of water supplies (Bergman and Matthews, 1983).

Some legal questions directly related to the practical consequences of implementing conjunctive use plans are:

e. Assuming that a legal - institutional framework can be achieved, how will the "new rules" of conjunctive use water management be enforced? There are numerous aspects of conjunctive use that call for supervision of legal - institutional arrangements by a central water authority. These authorities, employing enforcement officials such as watermasters, are needed to fulfill various functions. These might include: 1) the interpretation and enforcement of water use permits, and the implementation of emergency measures during water shortages; 2) the acquisition, construction, maintenance, management and operation of facilities and structures necessary for conjunctive use; 3) the coordination of recharge, withdrawal, conveyance and treatment of water from various sources (and subject to different ownerships); 4) in artificial groundwater recharge, the accounting of water stored in an aquifer (overlying landowners, local water utilities, and regional and state agencies -- e.g., Metropolitan Water District and the Department of Water Resources in southern California -- may be using the aquifer at the same time); 5) the levy of assessments on users of conjunctive use facilities; 6) arbitration in disputes between the various agencies that are parties to a conjunctive use agreement (Coe, 1979, Threatt, 1984; Camp, Dresser & McKee, Inc., 1983).

f. What is the impact of artificial groundwater recharge on the water rights of landowners when the owner's property overlies the recharge aquifer? Who owns the water after it is spread or injected and placed in storage? What are the legal

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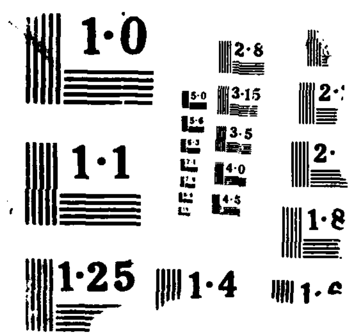
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rights of "third-parties" to abstract recharged water? What are the rights (of water agencies) to prevent others from exploiting recharged water? (Gleason, 1978). There is a general lack of precedent concerning ownership and control of recharge water, the right to recharge, the use of sub-surface space, the recovery of recharge water and of the consideration of underground storage of water as a beneficial use (Coe, 1979; Enson and Dixon, 1984).

g. What entity involved in water supply, delivery and wastewater reclamation actually owns reclaimed effluent and has the right to store (i.e., recharge), reuse it or sell it? Unlike other potential water sources, reclaimed effluent has been through a sequence of ownership. Any number of agencies -- the supply utility that appropriates and sells water, the municipality that treats and distributes water, the local sanitation district or wastewater treatment facility that renovates the water -- could conceivably claim ownership of the effluent (Schneider, 1985).

h. What is the legal position concerning the modification of groundwater quality by artificial recharge, especially recharge with wastewater effluent? Recharged water may cause harm to users of extracted groundwater; such harm could be in the form of personal injury, property damage or economic loss. Legal action that may be taken could involve many plaintiffs, many defendants and many theories of liability. There is the potential liability of the supplier caused by negligence or breach of warranty -- e.g., negligence associated with varying water quality; nuisance actions brought by public or private parties -- e.g., interference with public health, or interference with the use or enjoyment of land (Schneider, 1985).

i. What is the legal liability associated with any increased costs to water rights holders resulting from conjunctive management of water resources? For example, who should take the loss for any increase in subsurface outflows caused by conjunctive

use? (e.g., increased groundwater flows that may occur along streams being drawn down for aquifer recharge).

j. <u>What is the legal liability of possible structural and other damage caused by changes in ground water-table elevation</u>? For example, aquifer recharge may cause the water table to rise which could flood basements or waterlog agricultural land. Also, short-term fluctuations in water table elevations may exacerbate subsidence problems.

A myriad of legal questions. However, as discussed in the following section, some states have already tackled -- and, to some extent, resolved -- some of these questions.

COURT DECISIONS

Important decisions by California courts in 1975 affirmed the right of public (water) agencies in California to use space in a groundwater basin as an underground reservoir to store imported water. The court decisions also stipulated that the stored water is protected (against expropriation by others) for later recovery and use, provided that the water is stored and extracted in such a way that it does not impair local groundwater rights (Camp, Dresser & McKee Inc., 1983).

a. Niles Sand and Gravel Company v. Alameda County Water District (1974, 1975), and City of Los Angeles v. City of San Fernando (1975):

These two cases judicially established four public rights that cover the general underground storage "issues" that are of utmost importance if California is to realize the full potential of conjunctive use/artificial recharge:

1. The right to store water in a natural underground basin without compensating overlying landowners;

2. The right to protect the stored water from expropriation by others and from inequitable operational burdens;

3. The right to recapture the stored water when it is needed;

4. The public's priority to store water underground when there is a shortage of underground storage space.

(Schneider, 1977, Gleason, 1978; Coe, 1979)

In the Niles case, the California Court of Appeals enjoined the Niles Sand and Gravel Company from pumping water from its gravel pits and allowing it to flow into San Francisco Bay. Since 1935, the Alameda County Water District has conducted a groundwater replenishment program in order to prevent saltwater intrusion, conserve local surface runoff, and regulate imported water supplies. Water from the District's recharge operations

seeped into the gravel company's pits and the company pumped water from the pits allowing it to "waste" into the bay. The appellate court in Niles agreed with the trial court that, under the correlative rights doctrine, overlying owners in the Niles basin must "refrain from discharging more than their reasonable share of the underground water ... ". The gravel company's pumping and discharge was deemed unreasonable because it was detrimental to the "water basin and the restorative program of the (water) district".

Niles also established that a public agency does not have to compensate overlying landowners for damage from seepage caused by raised groundwater levels, up to the point where the recharge operation returns the water table to its "state of nature" level. The elevation of a groundwater table is in a "state of nature" when it is in "that condition which would exist without diversion from the watershed and/or extractions from the basin ... ".

In the City of Los Angeles v. City of San Fernando case, Los Angeles filed suit against San Fernando to establish Los Angeles' ownership of all groundwater under the San Fernando Valley. The decision eventually handed down by the California Supreme Court found that Los Angeles had a pueblo right (Sax, 1965) to both the surface water of the Los Angeles River and the native groundwater in the San Fernando basin. The court also ruled that an importer (Los Angeles) has the right to recapture imported water that is recharged to the aquifer as a result of spreading operations or through percolation of return flows attributable to delivered imported water. The case established that the right to recapture water is in the highest priority category: "imported recapture rights and pueblo rights are equally paramount to rights based on overlying use and appropriative groundwater rights". The court also recognized that nonparty public agencies (i.e., agencies that are not parties to any recharge agreement) had the right to store water provided groundwater storage capacity was available

and that the water stored by the nonparty public agency did not cause any losses of water stored by party public agencies.

As in the Niles case, Los Angeles also established that an importer has a right to prevent others from pumping the imported water that reaches a groundwater basin. Moreover, the importer can have pumping by overlying owners and appropriators stopped when their pumping plus the importers' extraction of imported water overdrafts the basin.

No priority system for groundwater storage was established in Los Angeles, although the trial court "felt that such control of recharge operations was necessary and that the court should apportion the use of storage space to protect the public interest".

How do the two California court decisions, Niles and San Fernando, impact conjunctive use in that state? The most important consequence is that California courts have recognized the right of public agencies to store water underground. Aquifer storage of water, and the subsequent recovery of that water, is an important element of some conjunctive use schemes. Secondly, the right to protect stored water from other pumpers allows for the storage of water underground for long periods of time. Usually, water is placed in the aquifer during excess or "wet" periods and later withdrawn and used during drought or high demand periods. Finally, conjunctive use operations can benefit from the court rulings in that the "public" has priority to storage space in underground basins.

b. Chino Basin Municipal Water District v. City of Chino (1975): In another case of interest a suit was filed as a result of a declining groundwater table, deteriorating water quality, and the need for a legal framework to develop a management plan in the Chino groundwater basin (Coe, 1979). The judgment provided for 1) adjudication of all groundwater rights;

2) allocation of the decreed rights into three operating pools -- overlying producers who produce water for other than industrial and commercial purposes (pool A), overlying producers who produce water for industrial or commercial purposes (pool B), and owners of appropriative rights (cities, water districts, etc.) (pool C); 3) a watermaster with authority to administer and enforce the provisions of the judgement and any subsequent instructions and orders of the Court; 4) an advisory and three pool committees; and finally, 5) the use of excess storage capacity by nonparties with written approval of the watermaster.

The Chino judgement imposed a physical solution to the allocation problem: the safe yield of the Chino Basin was declared to be 140,000 AF/yr -- 59.1% of this quantity was allocated to pool "A", 5.3% to pool "B", and 35.6% to pool "C". Chino Basin Municipal Water District was appointed Chino Basin Watermaster and given various powers. These include the power to enter into agreements or contracts to facilitate any aspect of the judgement, and the power to levy assessments against pool members to purchase replenishment water as necessary. All actions, agreements, decisions and rules of the Watermaster are subject to review by the Court, the Watermaster itself, the advisory committee or any pool committee. The rules and regulations of the Chino Basin Watermaster were adopted at a public hearing in 1978. They emphasize the priority of storage for local use rather than storage for subsequent export, the requirement that no party shall be deprived of access to the groundwater storage because of unreasonable pumping by others, and the maintenance and improvement of water quality.

STATE LEGISLATION

The two state legislative acts reviewed in this section are 1) the 1980 Arizona Groundwater Management Act, and 2) the Colorado Water Rights Determination and Administration Act of 1969. Statements and provisions in these two Acts pertain directly or indirectly to conjunctive use. The Arizona Act, in particular, is an example of a modern comprehensive water management law, possibly similar to laws that could become the centerpiece of large-scale conjunctive use projects.

a. Arizona Groundwater Management Act of 1980 (abstracted from Briggs, 1983 and Ferris, 1983): After trying unsuccessfully for more than forty years to bring some orderly control to the use of groundwater resources, the Arizona Legislature in 1980 took a leadership position by passing this novel and far-reaching Act. Few had been satisfied with the status quo after the 1976 decision by the Arizona Supreme Court that restricted transportation of groundwater off the land in critical areas, and the Federal Government was beginning to link continued funding for the Central Arizona Project to some legislative action to control groundwater pumping. For years, increasing withdrawals of groundwater had led to a myriad of complex problems including land subsidence, water quality degradation and costly disputes between groundwater users.

The Arizona Groundwater Management Act falls short of providing legislation directly aimed at facilitating conjunctive use. The closest it comes is to allow the Department of Water Resources "to develop plans to augment water supply through watershed management, artificial recharge and 'other feasible means'." This activity can begin after the start of the second management period in 1991. However, in its current form, the Act does provide us with a glimpse of the "general form" of legislation that may be necessary to encourage far-reaching integrated management of water.

Provisions of the Act. The new law has two primary goals: the first is to control the severe overdraft of groundwater taking place in some parts of Arizona; the second is to establish an "allocation protocol" in an attempt to equitably distribute groundwater to meet the changing needs of the state.

"Active Management Areas" (AMA's) were established in four areas of Arizona where the rate of groundwater pumping was deemed severe enough to warrant intensive groundwater management. Approximately 80% of the state's population resides in these four areas, and they consume about 70% of Arizona's water. By focussing attention on these areas, users outside of AMA's are not subject to what for them would be unnecessary regulation. The goal for the three urban AMA's -- Phoenix, Tucson and Prescott -- is "safe yield" ... i.e., by the year 2025 withdrawals must not exceed recharge.

Within AMA's the code regulates both existing and future uses of groundwater. Persons who were using groundwater when the code was enacted may obtain a "grandfathered right" from the Department of Water Resources (DWR) allowing them to continue their withdrawals and uses. Sixteen thousand applications for grandfathered rights were subsequently received by the Department (Note: DWR was established by the Act, replacing the former Arizona Water Commission). A person may acquire a new right in three ways: 1) he may purchase a grandfathered right, 2) he may apply for a groundwater withdrawal permit, and 3) he may seek service from a municipal supplier (i.e., a city or private water company).

The law provides that farmers may retire their land and sell up to 3 acre-feet of groundwater per acre for other uses. The groundwater withdrawal permits have stringent prerequisites, including the requirement that an applicant must demonstrate that grandfathered rights and Central Arizona Project water are not available for purchase. Although cities and private water

companies are not directly limited in the amount of water they may pump (they are allowed to increase withdrawals from existing wells to serve new customers), they do not have unlimited authority to drill new wells and must demonstrate sufficient water to dramatically increase withdrawals.

Each AMA is subject to its own sequence of five management plans. Generally, each plan has more stringent requirements than its predecessors. Every sector of water user is required to introduce water conservation measures; farmers, for example, will be allowed to legally use only as much groundwater as is required to grow the crops grown historically, with the allowable quantity of groundwater being influenced by new agricultural use conservation practices. Municipal users will be required to achieve reasonable per-capita consumption reductions. Industrial users are required to use the latest "commercially available conservation technology". At the end of the first management plan (1990), the Director of DWR may develop plans to augment supply through watershed management, artificial recharge and "other feasible means." After 2006, the Director may also purchase and retire grandfathered rights in order to achieve the management goal.

Recognizing that agriculture consumes around 90% of the state's water, the Act bans new irrigated acreage in the AMA's. Also, urban development is prohibited if there is not an "assured water supply." Before selling land that is outside of a municipal or water company service area, the seller has to convince DWR that there is sufficient water to meet the needs of the lot (and any proposed development thereon). For the purposes of the Act, there has to be reasonable assurance of a 100-year supply. However, DWR uses an arbitrary water depth level for determining what constitutes an assured supply. If the pumping level is likely to drop below 1,200 feet after 100 years of use, or more than 10 feet a year, there is deemed to be no assured supply. Alternative criteria have also been suggested, including

the restriction of development in any area where the water table is already dropping at an "unacceptable" rate per year, or where the proposed development would cause the water table to reach that decline rate.

The code also requires that all persons withdrawing water in an AMA from wells with a pump capacity in excess of 35 gallons per minute must use an approved water measuring device. The Act provides for assessment of a fee not to exceed $5 per acre-foot, with the revenue helping to offset management costs.

The Act provides, for the first time in Arizona, stringent enforcement provisions. DWR is empowered to issue cease and desist orders to violators; back-up enforcement powers include civil penalties up to $10,000 per day of violation, and criminal penalties ranging from misdemeanors to felonies.

Criticisms. There have been a number of criticisms of the Act since its passage, and these are worthy of comment. The first relates to the claim that the law is very difficult to understand and interpret -- and this applies not only to the general public, but to lawyers as well (Pontius, 1983). It is perhaps inevitable, given the importance and complexity of water in Arizona -- including the political forces at work and various interest groups -- that the drafting of any significant new legislation evolves into a major undertaking.

Secondly, the retirement of agricultural land (permissible outside of municipal and private water company service areas), and the sale of its water rights is unlikely to occur in practice, largely because municipal water suppliers do not have to acquire grandfathered rights in order to supply new developments. There is also confusion surrounding cases such as the sale of agricultural water for golf course irrigation or recreational lakes -- is this allowable, or will DWR restrict such uses in its management plans on the grounds of water

conservation? There is doubt as to whether the ability to sell grandfathered rights can really be exercised without restriction. This is an obstacle that needs attention -- the water problem in Arizona would be substantially relieved if there was not such high agricultural use. Incentives are needed to retire agricultural land, and development plans that retire such land need to be given priority.

Another criticism of the Act is the claim that the legislation lacks flexibility. For example, the holder of a non-agricultural right <u>cannot</u> increase use above the total amount quantified, based on the highest annual usage between the years 1975 and 1980. An industry that has been pumping its own water cannot expand that water use, although it might be able to enhance its supply by receiving water from a municipality, if this is feasible, but it is undoubtedly more expensive to do this.

Although the Act allows municipalities, water companies and irrigation districts to pump from within their "defined" service area, no additional wells are allowed in new service areas. Consequently, in an attempt to get approval of the defined area, municipalities and water companies were submitting service area maps to DWR depicting comprehensive plans for future service areas. In addition to well location, two important provisions of the Act directly relate to the definition of service area: irrigation grandfathered rights cannot be sold or converted to other uses, nor new permits issued, within a service area. DWR tried to establish workable rules for well development outside of <u>existing</u> service areas, but discovered after two years that it was impossible to satisfy all the parties involved (especially affected neighboring water users). A recent court case affirmed that the Act does restrict the development of new wells outside of the existing service area; cities and private water suppliers can only develop new wells if there is an existing water

distribution system, or an existing connection to a distribution system.

The Act is claimed by some to discriminate unfairly against private water companies. Developers served by private companies have to prove that there is a 100-year supply; cities are presumed to have assured supply by the mere fact that they have agreed to buy import CAP water. The cities have a competitive advantage in the water business, and therefore in the competition as to where development will take place. Private water companies were not well represented in the negotiations that preceded the Act, and they are paying the price.

Court Challenges. There have been a number of court challenges to the Act. Plaintiffs in one case argued that "they own the groundwater beneath their land and that preventing their use of the water, the code took their property without compensation." They also argued that "some provisions of the code which treat water users differently were unconstitutional because the state had no rational basis for the difference in treatment." For example, the plaintiffs claimed that there is no justification for the distinctions the code makes between cities and private water companies or between mining and other industrial water users.

In the case, Cherry v. Steiner, the United States Court of Appeals for the 9th. Circuit affirmed all the decisions of the U. S. District Court judge who had earlier rejected all the plaintiffs claims. He found that under Arizona law, as previously announced by the Arizona Supreme Court, landowners do not own the groundwater beneath their land. In so ruling, he noted that assertions to ownership of groundwater were illogical since groundwater does not respect property boundaries and withdrawal by one landowner will necessarily interfere with withdrawals by adjoining landowners.

Since the Act contains a non-severability clause, a decision that even a single provision of the law is unconstitutional would void the entire Act. The circuit court's decision is viewed as a major victory for the State, upholding the total code against a significant legal challenge.

b. Colorado Water Right Determination and Administration Act of 1969 (abstracted from Morel-Seytoux, 1985): Unlike the Arizona Act, this 1969 Colorado Act was specifically intended to facilitate the conjunctive management of both surface and groundwater in a stream-aquifer system. The declaration of policy section of the Act includes the following statements:

> (1) it is hereby declared to be the policy of the state of Colorado that all waters originating in or flowing into this state, whether found on the surface or underground, have always been and are thereby declared to be the property of the public, dedicated to the use of the people of the state, subject to appropriation and use in accordance with law. As incident thereto, it shall be the policy of this state to integrate the appropriation, use and administration of underground water tributary to a stream with the use of surface water, in such a way as to maximize the beneficial use of all of the waters of this state. (2) Recognizing that previous and existing laws have given inadequate attention to the development and use of underground waters of the state, that the use of underground waters as an independent source or in conjunction with surface waters is necessary to the present and future welfare of the people of this state, and that the future welfare of the state depends on a sound and flexible integrated use of all waters of the state, it is hereby declared to be the further policy of the state of Colorado that in the determination of water rights, uses and administration of water the following principles shall apply: (a) Water rights and uses heretofore vested in any person by virtue of previous or existing laws, including an appropriation from a well, shall be protected subject to the provisions of this article. (b) The existing use of groundwater either independently or in conjunction with surface rights, shall be recognized to the fullest extent possible, subject to the preservation of other existing vested rights, ... (c) The use of groundwater may be considered as an alternate or supplemental source of supply for the surface decrees heretofore entered, taking into consideration both previous usage and the necessity to protect the vested rights of others.

These declarations set the stage for conjunctive use in Colorado. The policy presents a mandate to the Colorado State Engineer to maximize the relationship between surface water and groundwater for beneficial use. As is the case with the Arizona Act, this legislation has withstood legal challenges, the Colorado Supreme Court upholding the law in a decision handed down in 1971.

LEGAL QUESTIONS TO BE ADDRESSED

What legal questions should be addressed in a conjunctive use investigation? The earlier discussions on water law, current legal constraints to conjunctive use, and pertinent legislation and court decisions provide most of the answers to this question. What follows is an attempt to clearly specify the legal questions that should be asked.

a. What is the current status of state water law? Specifically:

What is the basic doctrine of water rights in effect for surface and groundwater resources?

What special features of legislation have amended the basic doctrine in order to accommodate needs and circumstances unique to the area?

What is the history of the evolution of water law, especially with respect to recently enacted legislation, proposed or pending legislation that addresses outstanding unresolved legal issues, and notable court cases that have set precedents for water use?

b. What are the legal obligations of water agencies?

Typically, a number of agencies are involved in water management, including state Departments of Water Resources, Water Commissions, local and regional entities established for water delivery, power, flood control, agricultural and other special improvement, soil and water conservation, irrigation water delivery, drainage and levee maintenance, etc., state Water Quality Control Boards and Departments of Health (water quality control). At the federal level, the Army Corps of Engineers, Bureau of Reclamation, Geological Survey, Department of Agriculture, Office of Management and Budget, and other agencies are involved in quantitative (as opposed to qualitative) aspects of water development.

c. What is the function of water agencies that may be parties to conjunctive use systems, especially their legal obligations, institutional structure, method of operation and interaction with other agencies; What methods are used

to administer, monitor and enforce water rights, and resolve water use conflicts?

Another fundamental task is that of evaluating the legal implications of feasible alternative plans for conjunctive use operations. Initially, the feasible plans might be those that satisfy only economic and engineering tests of feasibility. That is, the optimal planning approach is probably to formulate alternatives without regard -- in the first iteration of the planning process -- for any legal (and institutional) constraints that may eventually inhibit implementation of an alternative.

Once the alternatives that are feasible from an economic and engineering viewpoint have been formulated, the "ideal" legal framework can be clarified. The "ideal" legal framework is the one that permits optimal conjunctive use development. What will evolve is likely to be a simpler legal system for implementation, management and operation of the planning alternatives than currently exists in the study area.

Finally, an accommodation between the "ideal" and "practically achievable" legal systems has to be worked out. "Practically achievable" systems include existing laws and new legislation that would have a reasonable chance of being enacted into law. The accommodation can be approached in two different ways:

d. How do the proposed (ideal) features of the alternative conjunctive use plans need to be modified to accommodate a "practically achievable"legal structure? and, How does the existing legal structure need to be modified to accommodate the proposed features of the alternative conjunctive use plans? That is, what is necessary to move from the existing to the "ideal" legal systems?

Both approaches to the necessary compromise may be feasible. The first question may represent the approach that is easiest to implement. However, the second represents the preferred approach. In order to improve the chances of modifying existing laws it is important that the planning alternatives be carefully

prepared, with benefits, costs, modes of operation, future expansion potential, etc., being thorougnly analyzed and clearly presented. It is generally true that wise decisions can only be made if decision-makers have complete information on the planning alternatives. This is particularly true for conjunctive use projects, which tend to be more complex than other types of water resources developments.

Both questions represent involved, time-consuming investigations. Much of the investigation can be related to the perceived legal uncertainties outlined in an earlier section. Obtaining answers to those uncertainties provides substantial information on which to determine, what is, and what is not, feasible from a legal viewpoint.

Legal constraints represent one of the obstacles that have to be overcome in conjunctive use water management. Although the complexity of the task will vary from state to state, it is essential that study managers work closely with legal experts to develop planning alternatives that are both efficient and legally feasible. The consequences of facilities planning without due regard for legal or other issues can be serious, voiding as it may, many man-hours of work.

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INSTITUTIONAL NEEDS

The broad institutional need of conjunctive use can be defined as:

> To provide an effective and efficient organizational structure for planning, promotion, development and operation of an integrated (multiple source) water supply system.

Within this broad statement of institutional need are numerous specific needs. These may include:

1) Supervision and coordination of the development, operation, maintenance and replacement of conjunctive use facilities.

2) Provision of a means of coordinating the purchase of water, water rights, and of facilitating water transfers.

3) To equitably allocate costs and benefits between the partners (beneficiaries) in a conjunctive use project.

4) To maintain an accounting of allocated (available and in use) storage space in aquifers.

5) To act as an arbiter in disputes involving project partners, and in the resolution of unanticipated circumstances affecting the participation of one or more partners.

It is clear that there are many institutional factors that need to be examined. Most of them relate to the operation of a project. Institutional arrangements that evolve from the planning study will be directly associated with existing and desirable water-related legislation, water rights, political realities and the established responsibilities of existing agencies. The major institutional elements of conjunctive use

planning are shown in Table 2.

Water problems and their feasible solutions tend to be local or regional in nature. To better understand the institutional arrangements, three quite different case studies will be described. The case studies clearly demonstrate that institutional feasibility is strongly influenced by the provisions of existing water law and politically feasible, water-related legislation. Indeed, all successful institutional arrangements for conjunctive use are firmly founded on an appropriate legal framework. The legal connection overshadows all other institutional planning considerations for conjunctive use.

MAJOR INSTITUTIONAL ELEMENTS

Water storage & groundwater recharge agreements

Facilities operating agreements

Water rights

Project promotion

Political & community support

Water transfer agreements

Inter-agency planning

Cost-benefit allocation

Water use permits

Facilities maintenance agreements

Water markets

Water & wastewater purchase and sale agreements

Arbitration of inter-agency disputes

TABLE 2: Major Institutional Elements of Conjunctive Use Planning

CHINO BASIN, CALIFORNIA

One of the examples of conjunctive use facilities presented elsewhere in this document is the Chino Basin groundwater augmentation program in southern California. Feasibility of the plan has been studied by consultants to two major water institutions, the California Department of Water Resources (DWR) and the Metropolitan Water District of Southern California (MWD).

As outlined in the legal feasibility chapter, the function of the Watermaster appointed by the San Bernardino County Superior Court is to manage the water resources of the Chino Basin. The consultants recommended that for the storage and associated water exchange program to be institutionally feasible MWD should be the operating agency. Either MWD or DWR could be the sponsoring agency responsible for financing and managing the yield from the storage program. In addition, the following three institutional arrangements would be required:

1) MWD and the Chino Basin Watermaster would have to develop a storage agreement permitting the program to store and retrieve water from the Chino Basin.

2) MWD and local agencies involved in the two water exchange projects would have to develop exchange agreements that define the terms and conditions for project implementation.

3) An agreement should be reached between Orange County Water District (OCWD) and MWD to reimburse the storage program for the additional base flow in the Santa Ana River that OCWD is able to divert and store in Orange County groundwater basins as a consequence of the storage program.

By Court order, the Chino Basin Municipal Water District was appointed Chino Basin Watermaster with responsibilities to administer and enforce the provisions of the 1975 judgment (see

the legal feasibility chapter), and any subsequent instructions of the Court. The Watermaster's powers include the authority to enter into agreements or contracts to facilitate any aspect of the judgment, and the power to levy assessments against pool members to purchase aquifer replenishment water as necessary. The judgment provided for allocation of decreed rights into three operating pools -- overlying producers who produce water for other than industrial and commercial purposes, overlying producers who produce water for industrial or commercial purposes, and owners of appropriative water rights (cities, water districts, etc.). Three pool committees and a judicially-created advisory committee assist the Watermaster. The advisory committee must approve the Watermaster's proposals before they become effective.

The rules and regulations of the Watermaster were adopted at a public hearing in 1978. They emphasize the priority of storage for local use rather than storage for subsequent export, the requirement that no party shall be deprived of access to the groundwater storage because of unreasonable pumping by others, and the maintenance and improvement of water quality.

The rules and regulations provide the general guidelines for a storage agreement between the Chino Basin Watermaster and MWD for implementation of the groundwater augmentation plan. Moreover, they are clearly in the interests of the beneficiaries of the augmentation project, and protect the rights of others who may be affected. Hence, the probability of institutional, political and community support is maximized.

Institutional arrangements required for the water exchange projects are rooted in a 1980 judgment that created the "Water Facilities Authority", a consortium of cities and water districts established to cooperatively tackle their common problems of water supply. The Authority consists of one member of the governing board of each party to the agreement. Specific powers

granted under the judgment include:

1) To jointly exercise the common powers of members in studying and planning ways and means to provide facilities for the treatment and distribution of water to members.

2) To make and enter into contracts.

3) To acquire, construct, manage, maintain, and operate facilities and structures necessary to carry out the purposes of the agreement.

STATE OF NEW JERSEY

Many serious water supply problems exist in New Jersey, including shortages of water during droughts and other emergencies; contamination, especially of groundwater; and the problems of having over six hundred institutions (government agencies and privately-owned companies) supplying water to consumers. However, during the past ten years, New Jersey has designed and started to implement an ambitious water supply planning, regulatory and management program. Conjunctive use is an important component of the program.

Most of the functions of water management are carried out by the Division of Water Resources of the Department of Environmental Protection (DEP). The division's responsibilities include water supply planning, allocation of ground and surface water withdrawals, implementation of State and Federal safe drinking water standards, the construction grants program, and the National Pollution Discharge Elimination System permits program. Also included in the division are the state geological survey, and groups responsible for flood control, stormwater management, and flood-plain management. Included outside the division, but within the department, are the programs of waste management, coastal resources, and parks, forests, fish and game. The Water Supply Authority, largely under the control of the Commissioner of the Department of Environmental Protection, is responsible for construction and operation of state-owned water supply facilities, which currently number three (two storage reservoirs and an aqueduct).

The many serious water problems encountered in New Jersey over the years have given the state an advantage over many others: crisis-initiated water supply legislation and bond issues have given state agencies above-average levels of funding and strong regulatory authority. In particular, the Water Supply Management Act of 1981 established permits to withdraw water that

are a privilege rather than a property right. This is a key factor in the successful implementation of New Jersey's comprehensive water plan.

Although the State has wide-ranging powers to regulate water, the statewide water supply master plan (1982) gives the Division of Water Resources a coordinating, rather than a dominating role. The state, through its planning activity, outlines the nature of improvements that are required to provide sufficient water of adequate quality, places appropriate requirements on purveyors through regulatory measures, offers loans for specified programs, and provides funds to construct and operate needed facilities that the purveyors cannot, or will not, undertake.

The Water Supply Master Plan focuses on three areas of activity: rehabilitation of distribution systems, supply system interconnections and remedial work on contaminated well fields. The latter activity includes strategies for managing depleted aquifers that have not to date shown evidence of contamination. Of particular interest in this category are important coastal aquifers -- reduced groundwater levels allow encroachment of saline water from the Atlantic Ocean, and from bays and estuaries. Once an aquifer has been invaded with salt water, the wells affected may be regarded as destroyed.

New Jersey has been successful in developing an approach which requires reduced user withdrawals from depleted aquifers, while requiring all users to contribute to the necessary alternative surface supplies. All users will be given an annual withdrawal limit based on a reduction from actual total withdrawals for the year 1983. The reduction will equal the percentage by which total aquifer use in 1983 must be reduced so as not to exceed the total "dependable aquifer yield". The deficiency will be made up, for users connected to an alternative source, by purchase of surface water from that source, and for

users not so connected, by buying water from another source and having that water delivered not to them but to a connected user. This extra water enables the connected user to reduce groundwater pumping, while the unconnected user is given a supplemental allocation to withdraw more groundwater. This interesting and novel idea encompasses conservation, recharge and conjunctive use.

Although, as mentioned above, the Water Supply Management Act of 1981 gave the State broad authority to manage water on a statewide or regional basis, it was decided that a blanketing extension of management control over six hundred water supply entities was not the best approach. Regulations were issued which make only a few demands on water institutions generally, but which concentrate attention on water supply critical areas designated by DEP. Three critical areas have been identified to date (Middlesex - Monmouth - Ocean Counties, Metropolitan Camden, and Atlantic County). All three are within the coastal plain, and tap confined aquifers having limited natural recharge capacity. An extensive modelling study is underway, in cooperation with the U. S. Geological Survey, to determine the long-term "safe yield" of the first critical area (Middlesex - Monmouth - Ocean Counties (MMOC), a rapidly-growing area south of metropolitan New York; MMOC was designated critical water supply area #1 in July 1985).

A storage reservoir is planned for the southern half of critical area #1: the Manasquan Project, funded under the Water Supply Bond Act of 1981 and costing $72 million, will be built and operated by the Water Supply Authority. It will provide about 30 million gallons a day during a repetition of the most severe drought on record. In the north of the area, a feasibility study, funded under the 1981 bond act, is examining economic growth, projected water needs, structural alternatives and institutional issues. Some water agencies and companies, even a private entrepreneur, have initiated new supply pipelines,

a recharge project and a new surface diversion. The latter is to be used in a conjunctive mode with wells.

The regional management plan recognizes that these new sources of water cannot physically be connected to all the existing wells and distribution systems in critical area #1. However, it is also recognized that all users must share equitably in the cost of bringing in alternative supplies to replenish a depleted aquifer. Hence the "connected users" and "unconnected users" idea. The State retains authority to mandate connected suppliers, through conditions of their withdrawal permits, to accept up to 20% of their base allocation in the form of surface water paid for by others (unconnected suppliers).

The 1981 legislation requires all public water suppliers in New Jersey to provide for a system dependable yield equal to the total demands of their customers. In critical area #1, water deficiencies created by the lowered pumping limit may be made up by additional supplies from non-critical aquifers, by purchase of Manasquan project water, or by water obtained from other acceptable sources. Part or all of the deficit can be made-up through the implementation of conservation programs (although only a very small part -- less that one per cent -- of the state's 1981 bond issue is earmarked for the promotion of conservation plans).

Conjunctive use will be an important feature of the state's supply network. As the base groundwater withdrawal limit can be pumped at any time of the year, supplemental surface water (e.g., flood flows) will be valuable and may -- quality considerations aside -- have a higher priority than well pumping. It is not planned to increase groundwater pumping in drought years on the expectation that the extra volume pumped will be recharged on a 1-to-1 ratio during subsequent wet years. Concern over salt water encroachment does not favor the continuation of even short-term groundwater "mining", although extreme conditions may

necessitate additional pumping.

New Jersey's approach to regional water management has not led to a sweeping reorganization of the multitude of water supply institutions. The State gives suppliers flexibility within broad guidelines backed up by strong legislation and funding support. It is an approach that emphasizes water exchanges, conjunctive use, aquifer protection, system interconnection and rehabilitation. It is an approach that probably has many applications in other areas of the nation.

CITY OF VIRGINIA BEACH, VIRGINIA

Given two alternative plans for augmenting an urban water supply -- one consisting of a 100-mile long 60-mgd pipeline, two pump stations, etc., in total costing $125 million (1982); the other a 30-mgd conjunctive use project comprising pipelines, pumps and a small storage reservoir, in total costing $64 million. Why would the first alternative be the optimal choice? Both alternatives would have about the same effect of relieving a projected water supply deficit. The reason that the less efficient economic alternative might be chosen is because it may represent "the path of least institutional resistance".

The New Jersey case study demonstrates the initiative of that state in providing a comprehensive plan for management of its water resources. In Virginia, water management problems are in part due to institutional and legal questions surrounding water rights, water transfers between jurisdictions, and a need for adequate technical information on such items as aquifer yield, and the effect of proposed river abstractions on lake levels and instream flows (Shabman & Cox, 1986).

Several years of conflict over expanding the urban water systems of southeastern Virginia preceded the criteria for selection of the more expensive alternative. Although interdependent, the criteria were distinguishable; the city of Virginia Beach sought alternatives to (1) minimize the use of groundwater, (2) minimize the need for regional drought management, (3) minimize the likelihood of successful legal or administrative challenges, and (4) minimize the effects of water use projection errors. As it turned out, cost was not an important criterion: although the two alternatives cited above are significantly different in cost, the $60 million difference translates into an additional annual cost of $32 for a household using 5,000 gallons a month in 1990.

Unregulated use of groundwater in the early 1970's prompted passage of the Virginia Groundwater Act of 1973. The Act requires a state permit for groundwater withdrawals within designated areas, including the Atlantic coastline. Subsequent to the Act becoming law, an interpretation by a state Attorney-General ruled that groundwater withdrawals for public supply are covered by the Act's exemption for domestic use and are outside state permit authority. The water rights of public suppliers within management areas therefore remained subject to the state's common law. Neither the Groundwater Act nor the courts have addressed the rights of groundwater permit holders vis-a-vis common law rights. Moreover, common law groundwater rights themselves are not clearly defined; the Virginia Supreme Court appears to favor the reasonable use doctrine, which prohibits export of water for off-site use if other users of the aquifer are adversely affected.

Effective water rights markets would require a distinct move away from the common law system of water allocation. The first step in the transition would be to quantify water rights into withdrawal permits. In Virginia, the legislature has consistently rejected such proposals. However, in Virginia and other states with abundant water resources, the benefits to be derived from state-wide adoption of water rights markets would probably not justify the monetary and political costs. Few public water purveyors would take advantage of market exchanges, even in drought situations.

Challenges to implementation of a water supply alternative may be brought by administrative or court proceedings. In the present institutional setting in Virginia, there are two primary bases for such challenges: 1) socially unacceptable environmental impacts under section 404 of the federal Clean Water Act, and 2) a new project's interference with existing water rights.

There is often an urgency to develop additional water system capacity. This was certainly true for Virginia Beach, which sought an alternative which would minimize the success of any environmental or court challenge. The pipeline alternative, tapping an abundant water source, satisfied this goal. The conjunctive use plan would be likely to perpetuate historical conflicts, especially over groundwater withdrawals. New surface water development would require regional political negotiations, thereby raising the potential for riparian and environmental challenges.

Possible institutional reforms in Virginia to facilitate improved water management, including the implementation of conjunctive use projects, are: 1) extending permit coverage in designated management areas to all withdrawals (i.e., common law rights would be superceded); 2) increased power to the state's Water Control Board to regulate groundwater use, including the authority to permit withdrawals under conditions that may currently be interpreted as detrimental to other aquifer users (when the board considers further increases in the withdrawal rates inadvisable, permits could be transferable to other uses); 3) parties adversely affected by new withdrawals are entitled to compensation, with formal procedures set up by the water control board; 4) institution of a water transfer permit authority to approve all proposed transfers of untreated water across local political boundaries for public use (the authority would act as an adjudicatory body for resolving conflicting claims associated with a transfer, providing a binding solution on all parties); 5) actively and effectively seek answers to technical questions about the state's water resources (the state must act to limit local and regional disputes over technical matters).

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CONCEPTUAL BASIS

The conceptual basis for evaluating benefits for the various purposes of water resource development is presented in the Principles and Guidelines (U.S. Government, 1983). Three types of benefits are considered: the first is the value of goods and services resulting from a plan in which the general measurement standard is "willingness to pay": "Such a value would be obtained if the 'seller' of the output were able to apply a variable unit price and charge each user an individual price to capture the full value of the output to the user. Since it is not possible in most instances for the planner to measure the actual demand situation, four alternative techniques can be used to obtain an estimate of the total value of the output of a plan: 1) willingness to pay based on actual or simulated market price; 2) change in net income; 3) cost of the most likely alternative; and 4) administratively established values (e.g., unit-day values for recreation)".

a. Most likely alternative. For municipal and industrial supply, direct measures of willingness to pay are usually not available: "Where the price of water reflects its marginal cost, use that price to calculate willingness to pay for additional water supply. In the absence of such direct measures of marginal willingness to pay, the benefits from a water supply plan are measured instead by the resource cost of the alternative most likely to be implemented in the absence of that plan" (U. S. Government, 1983, p. 23). The alternative selected for the estimate of benefits must be a realistic alternative that could, and most likely would, be undertaken in the absence of the considered project. This includes projects that do not completely eliminate the projected gap between supply and demand, but balance the risk of occasional shortages against the savings from smaller investments.

b. Nonstructural measures. "The benefits from nonstructural measures (for M&I supply) are also computed by using the cost of the most likely alternative. However, the net benefits of certain nonstructural measures that alter water use cannot be measured effectively by the alternative cost procedure for the following reasons: (1) structural measures and many nonstructural measures (except those that alter use) result in similar plan outputs, whereas use-altering measures (e.g., revised rate structures) may change levels of output; and (2) use-altering measures may have fewer direct resource costs than measures based on higher levels of output. Because of this lack of comparability, the benefit from such use-altering non-structural measures should not be based on the cost of the most likely alternative" (U.S. Government, 1983). Many conjunctive use plans are essentially nonstructural in nature, being based more on modified management of existing water supply projects. Elements of some plans may "alter water use," and this can complicate the economic analysis by ruling out use of the most likely alternative approach.

c. Other benefits. In addition to the value of goods and services directly attributable to the water development project, there may be benefits due to unemployed and underemployed labor resources. "These benefits are conceptually an adjustment to the cost of the project. However, as this approach can lead to difficulties in cost allocation and cost-sharing calculations, the effects from the use of such labor resources (in project construction) are treated as additional benefits resulting from a plan." The third form of benefit is the external economies that are secondary direct effects of a project. They include incidental increases in the output of goods and services, and incidental reductions in production costs.

d. Costs. Resources required or displaced for project construction and/or operation, maintenance and replacement activities represent an NED cost, or "adverse NED effect"

(Petersen, 1984, p. 89), (U. S. Government, 1983, p. 10). In addition, resources required or displaced to minimize the adverse impacts and fish and wildlife habitat losses are evaluated as NED costs. Other than these two categories, no other costs are considered. Implementation outlays include costs incurred by "the responsible federal entity and other federal and non-federal entities for implementation of the plan in accordance with sound management principles." Such costs include:

1) Post-authorization investigation, survey, planning and design costs, based on actual current costs incurred for carrying out the same activities for similar projects

2) Construction costs, based on current contract bid items in the project area or the current market value of purchased materials, services, etc.

3) Contingency costs, based on estimates of unknown potential difficulties (ranging from 10% to 25%, depending on the estimated total value of the project and the stage of project work under consideration)

4) Interest during construction (usually set equal to the construction cost times the interest rate times one-half the construction period in years). No interest charge is assessed when the construction period is less than two years, or if benefits accrue as the work progresses. NOTE: no interest during construction is included for future additions to a project

5) Fish and wildlife mitigation costs

6) Relocation costs for highways, railroads, and utility lines

7) Historical and archaeological salvage operation costs (limited to not more than 1% of construction cost)

8) Land, mineral and water rights costs, based on current market values. The value of land easements is based on the difference in market value of land with and without the easement

9) OM&R costs, based on actual current costs for carrying out such activities for similar projects. Operation and maintenance costs include salaries for operating personnel; cost of labor, plant and supplies for ordinary repairs and maintenance; supervision; overhaul and periodic inspection. Replacement costs include the estimated costs of replacing the major components of a project

Associated costs are the indirect costs associated, but not directly attributable to, the project. For example, the cost of irrigation water supply laterals necessary to realize the computed irrigation benefits. Other direct costs include the cost of resources required to implement a project but for which no implementation outlays are made. This would include the value of federally-owned lands required for reservoir construction. Also included are "external diseconomies", or uncompensated NED losses such as increased downstream flood losses caused by channel modification, or increased water treatment costs caused by low quality irrigation return flows.

CONJUNCTIVE USE BENEFITS AND COSTS

There are two primary objectives of conjunctive use projects: (1) to improve the utilization of water resources (increase yield), and (2) to maintain an acceptable level of water quality. Of the six conjunctive use projects described under facilities the primary purpose of three (Chino Basin, California; Phoenix metropolitan area, Arizona; Sterling, Colorado) is to increase yield. Two projects (Tacoma, Washington; Water Factory 21, Orange County, California) are primarily intended to maintain acceptable water quality. The conjunctive use project in Elgin, Illinois, has a dual role of maintaining acceptable water quality and increasing yield.

Different conjunctive use projects increase yield or maintain quality in different ways. It is necessary to define how the general goals of conjunctive use are achieved in order to assign values to separable project benefits and costs. The types of benefits derived from conjunctive use are described below:

1) Increased water availability. Integrated use of various (i.e., two or more) water sources can increase total yield. The flexibility to move water between storage facilities, including aquifers, reduces 'losses', and therefore increases total water availability. Groundwater recharge of excess (e.g., flood) surface streamflows is an example (e.g., Chino Basin; Sterling). Control of groundwater migration through artificial recharge can also increase usable groundwater reserves (e.g., saltwater intrusion prevention, Water Factory 21). Reclamation and reuse of wastewater effluent is an important 'new' source of water (e.g., Phoenix metropolitan area).

2) Improved supply reliability. Use of multiple water sources reduces risks associated with reliance on only one supply source. For example, increased withdrawals from aquifers (or

increased use of import water) can compensate for low streamflows (e.g., Phoenix; Elgin).

3) Improved use efficiency of existing infrastructure. Integration of previously autonomous supply systems can increase the productivity of existing storage, transportation and treatment facilities (e.g., Phoenix). For example, combined operation of physically separate sources can utilize distribution systems already in service (sometimes aquifers themselves can be used as a transport facility).

4) Phased development of new supply infrastructure. The increased yield and higher reliability associated with conjunctive use mean that new facilities can be built on an 'as-needed' basis. The idle capacity potential of new projects is reduced. Phased development lessens the need for expensive 'up-front' financing as expansions to supply infrastructure are scaled more closely to changes in demand. There is the possibility of reduced investment in wastewater treatment facilities when (partially-treated) effluent is recharged to groundwater.

5) Improved management efficiency of integrated water supply operations. Possibility of streamlining operations and management functions if previously separate agencies (or agency divisions) are merged. If more efficient operations are <u>not</u> feasible within the structure of existing agencies, additional costs may be incurred if a new administrative unit is required to oversee conjunctive use operations (e.g., Chino Basin Watermaster).

6) Improved flexibility to manage fluctuations in water quality. The quantity of water drawn from each source in a multiple source conjunctive use project can be adjusted to compensate for fluctuating quality in one or more sources (e.g.,

Tacoma; Elgin). This benefit can reduce the need for new water treatment facilities.

7) Secondary benefits. Secondary benefits include the value of the ability to allocate higher quality (surface) water to more valuable purposes -- e.g., replacing surface water previously used for greenbelt irrigation with artificially recharged wastewater effluent. Also included are benefits due to the following consequences of artificial recharge conjunctive use projects: no evaporation loss from surface water recharged to aquifers (helps increase yield); reduced pumping lift when aquifers are used to store water (helps reduce pumping cost); reduced rates of ground subsidence (lessens structural damage); control of saltwater intrusion in coastal aquifers (a primary benefit in some projects).

MEASUREMENT OF ECONOMIC BENEFITS

The previous section defined the benefits of conjunctive use in qualitative terms. The question now is "how are the benefits of conjunctive use projects assessed quantitatively?"

It is clear that increased yield, improved supply reliability and the maintenance of acceptable water quality each have an economic value. However, the nature of conjunctive use projects is such that the direct measurement of these values is often more difficult than the measurement of benefits of more "classical" water projects. Conjunctive use projects often evolve as attractive alternatives for enhancing municipal and industrial (M&I) water quantity and quality in established urban areas. It is not necessarily straightforward to measure the value of water in these demand sectors: municipal water supply has a wide-ranging stimulus on the urban economy it serves, and moreover, urban water pricing policies do not usually reflect the full value of water to the user.

The usual method of evaluating M&I conjunctive use benefits is to compare project costs to the costs associated with alternative plans that accomplish the same objectives. This approach will probably always give conjunctive use alternatives an economic advantage over non-conjunctive use plans. The reason for this is the fact that most conjunctive use plans utilize existing facilities to some extent, and because integrated use of existing sources is clearly more efficient than satisfying increased water demand exclusively through development of new sources.

The economic benefit of the Chino Basin groundwater augmentation program (See Facilities chapter) is the value of the estimated 184,000 acre-feet of water by which the program will increase the annual firm yield of the California State Water Project. There are also relatively minor benefits from a 20 MW

hydropower plant that is proposed to be located at the end of a new transmission pipeline that supplies water to recharge wells. Alternatives to the groundwater storage program could include surface or above-surface storage facilities, increased capacity of the SWP aqueduct above that proposed for the recharge program, seawater desalination, and groundwater recharge of reclaimed effluent. If each alternative provides an additional 184,000 acre-feet per year, each has the same economic benefit as the groundwater augmentation program. The costs, however, will be distinctly different.

The benefits associated with the river water/groundwater project in Tacoma, Washington are the savings that the integrated system provides to the city compared to the costs of alternative ways of overcoming the Green River springtime turbidity problem. The alternatives included developing a completely new surface water source, or providing treatment plant processes to remove turbidity.

The conjunctive use project in Sterling, Colorado is not for M&I water supply, but for storing and treating excess streamflows in the winter season for use by irrigated agriculture during the following summer. Benefits may be computed directly as the value of the additional water (currently 280 acre-feet per year) to the local farming community.

COSTS ASSOCIATED WITH CONJUNCTIVE USE

Cost estimating procedures for conjunctive use facilities are similar to those for other water resource facilities and include estimates of materials, labor and other related costs. The types of costs are also similar: capital costs, replacement costs, operating costs, etc. What is different and unique are the specific facilities which make up a conjunctive use plan. These will vary depending upon the specific nature of the plan. The general types of costs associated with conjunctive use are identified below.

1. Capital cost of facilities necessary to implement conjunctive use: New facilities, or upgrading or rehabilitating existing facilities, to accommodate new water transport, storage and treatment needs.

2. Other implementation costs; operating costs: Facility planning, design, maintenance and replacement costs. Contingency and construction interest costs. Fixed and variable operating costs.

3. Cost of land, or easements, required to facilitate conjunctive use: Some elements of conjunctive use projects are very land-intensive. For example, surface-spreading basins for artificial recharge of groundwater.

4. Cost of purchasing water, or water rights, necessary to facilitate conjunctive use:

5. Energy costs: The supply 'flexibility' of conjunctive use projects implies that a greater volume of water might be transported (transferred) between facilities than in more conventional supply systems. Water pumping plants tend to be large consumers of electrical power (the California Department of Water Resources is the largest consumer of electrical power in

that state). Recharge injection (and additional abstraction) wells also consume energy.

6. Costs associated with a transition to conjunctive use operations: Cost of developing more complex planning, management and operations policies, especially for establishing a legal/institutional framework for conjunctive use involving more than one independent agency.

7. Cost allocation: Conjunctive use projects that involve a number of independent agencies (e.g., Chino Basin; Phoenix metropolitan area) need to have an equitable mechanism for distributing project costs.

8. Secondary costs: Environmental mitigation costs (fish and wildlife issues). Transportation and utility relocation costs. Historical and archeological salvage costs.

Costs associated with the following consequences of artificial recharge conjunctive use projects: degradation of groundwater quality caused by artificial recharge (a benefit if groundwater quality is improved; however, artificially recharged water tends to contain more dissolved salts than does native groundwater. There is also the possibility of unintentional chemical reactions between the injected and native waters); cost of 'lost' water (i.e., recharged water migrating out of the capture zone); costs of increased subsurface outflows (e.g., along streams being drawn down for aquifer recharge; this may increase pumping costs for riparian or other users); cost of structural or other damage caused by significant changes in water-table elevations (e.g., waterlogging of agricultural land or flooding of basements). Some conjunctive use projects reduce, or eliminate, the future need for surface reservoirs; this would reduce the potential for hydroelectric energy production.

SANTA CLARA VALLEY, CALIFORNIA

Reichard & Bredehoeft (1984) place the primary benefits of artificial recharge into two categories: those benefits which are a direct result of a reduction in the net rate of groundwater withdrawal (e.g., reduction of pumping lifts; reduction of land subsidence; prevention of seawater intrusion), and benefits associated with using the groundwater system rather than surface facilities for storage, treatment and conveyance. Notable secondary benefits in the Santa Clara study include recreational amenities: some of the thirteen recharge ponds form part of park and recreation complexes.

Reichard & Bredehoeft (1984) also list the costs associated with artificial recharge using infiltration ponds (spreading basins): water costs; land costs; construction costs of ponds and works; O&M costs of ponds; construction costs of conveyance structures and pumping facilities to transport water to recharge sites (if needed); and, energy costs of transmitting water to recharge sites (if needed). If recharge is used as an alternative to surface storage, the energy costs of pumping recharged water back out of the aquifer and the costs of abstraction wells must also be considered.

The Santa Clara study describes two economic analyses that were based on the results of a numerical groundwater simulation model developed at the U. S. Geological Survey and applied to the Santa Clara Valley using historical data on groundwater levels for model calibration and execution. The first analysis (artificial recharge vs 'no project') considered the benefits associated with a reduction in the net rate of pumping. Annual pumping and recharge rates of 150,000 and 100,000 acre-feet respectively were examined by the model. The benefits of reduced pumping lifts were calculated in terms of savings in energy costs, starting from the basis that a 100% efficient pump requires 1.02 kilowatt-hours of electrical power to lift one

acre-foot of water through one foot. Assuming an average pump efficiency of 54% and an energy cost of $0.06 per kwh, the unit pumping cost is computed as $0.113/acre-foot/foot. Annual benefits due to reduced pumping lifts were computed at approximately $1.68 million per year. These benefits should be increased for those cases where it would be necessary to incur costs to deepen wells in the 'no project' option.

It is often difficult to obtain a reliable value of the cost of land subsidence. For the Santa Clara Valley, where subsidence at the valley center has averaged 8 feet, Reichard & Bredehoeft (1984) quote a range of costs from $15 million to $131 million. This expense is for repair of damaged well casings, sewers, bridges, building and raising levees, and for the construction of drainage pumping stations. For the purposes of pursuing the economic analysis a value of $70 million was selected; this yields an average unit cost of subsidence of $8.75 million/foot. As the recharge program reduced the rate of subsidence by an average of 1 foot, total subsidence-related undiscounted benefits were taken as $8.75 million. As most subsidence takes place during the early stages of aquifer pumping this sum was then discounted one year to give a present worth value of $8.2 million (7% discount rate) at the beginning of the period of analysis. It follows that the benefits from reduced subsidence are significantly greater if an artificial recharge program is initiated at the same time groundwater pumping begins.

The total discounted costs of artificial recharge over 40 years were estimated at $10.4 million for land ($32,000/acre * 324 acres), and $6.4 million for operations and maintenance ($4.80/acre-foot * 100,000 acre-feet/year). The total discounted cost was, therefore, approximately $17.0 million. The discounted benefits of subsidence reduction ($8.2 million) and pumping lift reduction ($22.4 million) were $30.6 million. This simple analysis yields a benefit/cost ratio of 1.82 for first of the two analyses (reduction in the net rate of pumping). However, it

must be noted that the cost of purchasing water was not included in the analysis: an assumption was made that a decision had already been taken to purchase the water regardless of whether a recharge project was implemented or not.

The second economic analysis in the Santa Clara study sought to determine whether artificial recharge was the most economical way to accommodate additional supplies of water in the basin. The cost of land for infiltration ponds, and costs associated with the operation and maintenance of those ponds were the same as for the first analysis ($10.4 million and $6.4 million, respectively). However, the cost of pumping the stored water from the aquifer must now be included. Assuming an average pumping lift of 150 feet, the annual cost of pumping was computed to be $1.70 million ($0.113/acre-foot/foot * 150 feet * 100,000 acre-feet/year). Pumping 100,000 acre-feet per year would require forty-five 2000 gpm wells in operation about 70% of the time. Annual maintenance costs were set at $1,500 per well, for an annual sum of $67,500. Allowance was made to replace wells after twenty years at a 1982 cost of $100,000 per well.

The alternative to groundwater recharge would be to store the 100,000 acre-feet per year in surface storage, treat it in treatment plants, and transport it to users via pipelines and/or canals. The analysis assumed that the full 100,000 acre-feet would need to be accommodated in new facilities; however, it was acknowledged that the storage requirement could be reduced through modified (improved) operation of existing facilities.

Estimates of the cost of reservoir yield in the Santa Clara Valley range from $77/acre-foot/year to $430/acre-foot/year. These figures include operating costs and amortized capital costs. The study assumed that a value of $150/acre-foot/year was reasonable; this results in an alternative storage cost of $15 million/year. Treatment for 100,000 acre-feet per year necessitates a treatment plant capacity of 180 mgd. The analysis

assumed that treatment plant capacity costs $500,000/mgd, which yields a capital cost for treatment facilities of $90 million. Fixed O&M costs were computed at $2.0 million/year ($11,300/mgd/yr * 180 mgd), and variable O&M at $1.44 million ($14.40/acre-foot * 100,000 acre-feet/year). Finally, a network of pressure pipelines to convey water to 'demand locations' was considered to be equivalent to approximately 16 miles of 3-foot diameter reinforced concrete pipeline. The capital cost of such a line was computed as $14.78 million (84,480 feet * $175/foot). Annual pipeline O&M was computed at $88,700/year, or 0.6% of capital costs. The study assumed that the aquifer itself would be the transport mechanism for recharged water, and the distribution network would only be necessary in the surface system alternative.

Summing all cost components places the present worth of recharge costs at $50 million and surface facility costs at $352 million. As in the first analysis, the computations assumed a discount rate of 7% and period of analysis of 40 years. However, it must be noted that most of the capital facilities required for artificial recharge were already in place in the Santa Clara Valley; such facilities include natural infiltration basins and existing wells. If this were not the situation, basin and well construction costs would have to be considered, and the significant cost advantage enjoyed by the recharge plan would drop from a factor of 7.0 to 2.3.

The results of the first economic analysis indicate that the discounted benefits derived from reduced average pumping lifts and reduced land subsidence exceed the discounted costs of continuing the recharge program. The second analysis indicates that the cost of an alternative program of surface storage, treatment and conveyance would be considerably more than the costs of continuing to recharge water to the aquifer. Both analyses compare the cost of a conjunctive use (artificial recharge) plan with the cost of the alternative most likely to be

implemented in the absence of the plan; thus they comply with the requirements of the Principles and Guidelines in computing the M&I supply NED plan (U.S. Government, 1983).

CHINO BASIN, CALIFORNIA

One of the best-documented planning studies for artificial recharge was undertaken for the Chino Basin groundwater storage program in Southern California (Camp, Dresser & McKee Inc., 1983). Table 3 presents a breakdown of the capital costs for the three projects that constitute the recharge plan. The capital cost, if all three projects are implemented, is estimated at $89 million (January 1982 dollars). The largest single cost is for enlargement of the East Branch of the California Aqueduct ($25.82 million, 39% of the total construction costs). The cost of the aqueduct enlargement is allocated to the three projects in proportion to their respective yields. Thirty-three extraction and eleven dual purpose injection-extraction wells represent 27% of the construction costs ($17.57 million). Well construction is to be phased over time. New pipelines, including a 48 inch diameter delivery line six miles in length for project 'B', have an estimated cost of $10.93 million (17%).

Table 4 shows the estimated operation and maintenance costs for a 50-year period. The actual O&M costs incurred in most recharge projects will vary considerably from year to year depending on storage and pumping operations. In Table 4, variable costs (basically for treatment chemicals) represent 23% of the total O&M costs; these costs are only incurred when water is being injected or spread. Power costs are based on a unit cost of $0.08 per kilowatt-hour, and constitute 57% of the total O&M costs. Nearly all of the power costs are incurred during pumping operations; in fact, the 20 MW hydropower facility in project 'A' generates revenue-earning power surplus to the needs of the injection well pumps. Table 4 does not include the cost of delivering State Water Project (SWP) water to the Chino Basin from northern California. Capital cost and energy savings realized by water agencies participating in the storage program are also not shown in Table 4. These savings are substantial: an

Cost Category	Project A	Project B	Project C	Total
East Branch Enlargement	$15,300,000	$ 8,610,000	$1,910,000	$25,820,000
MWD Connections	1,280,000	410,000	250,000	1,940,000
Spreading Ground Improvements	2,930,000	-0-	250,000	3,180,000
Pipelines	2,430,000	7,880,000	620,000	10,930,000
Wells	9,220,000	6,100,000	2,250,000	17,570,000
Water Treatment Plant	4,110,000	-0-	-0-	4,110,000
Power Recovery Facilities	2,230,000	-0-	-0-	2,230,000
Total Construction Cost	$37,500,000	$23,000,000	$5,280,000	$65,780,000
Engineering, Administratio & Contingencies	13,130,000	8,050,000	1,850,000	23,030,000
Land	200,000	-0-	-0-	200,000
Total Capital Costs	$50,830,000	$31,050,000	$7,130,000	$89,010,000

TABLE 3: Breakdown of Capital Costs

Cost Category	Costs ($1,000's) Project A	Project B	Project C	Total
Fixed O&M				
MWD Connection	$ 290	$ 130	$ 60	$ 480
Treatment	8,050	0	0	8,050
Pipelines	0	400	30	430
Wells	4,130	3,050	1,120	8,300
Spreading Grounds	5,000	0	1,250	6,250
Power Recovery	2,670	0	0	2,670
	20,140	3,580	2,460	26,180
Variable O&M				
Spreading	4,190	0	1,020	5,210
Treatment	3,910	20,970	0	24,880
	8,100	20,970	1,020	30,090
Power				
Treatment	3,600	0	0	3,600
Wells				
Injection	(13,010)	(4,480)	0	(17,490)
Extraction	55,070	26,620	6,430	88,120
SWP Transportation (net)	10,430	2,980	3,210	16,620
Power Recovery	(17,620)	0	0	(17,620)
	38,470	25,120	9,640	73,230
Total O&M	$66,710	$49,670	$13,120	$129,500
Total Water Production (AF)	826,400	520,000	125,600	1,472,000
Unit O&M Cost Per AF	$81	$95	$104	$88

TABLE 4: Estimate O&M Costs over a 50-year Period

increase in water table elevation (averaging around 200 feet under maximum storage conditions), and the corresponding reduction in pumping lift, is estimated to translate into energy savings of $72 million over the 50-year design life of the projects. Adverse environmental/economic impacts of the recharge program include an anticipated 'slight' deterioration in the quality of (recharge-induced) baseflow in the Santa Ana River downstream of Chino Basin (as measured by TDS concentration). Two basic factors may cause a change in levels of TDS: imported water will be of a different quality than local supplies, and as groundwater levels rise, salts that have been deposited in the unsaturated zone by past land use practices could be picked up by the stored water. The deterioration in quality may impact the operations of the Orange County Water District.

The Chino Basin plan is one of a number of alternative plans to increase the firm yield of the SWP under investigation by the California Department of Water Resources. In order to compare the relative economics of the Chino Basin proposal with alternative investments, expected costs over a fifty-year interval (1986-2035) were evaluated using present worth analysis. The analysis is summarized in Table 5, in which equivalent annual costs are based on a capital recovery factor of 0.08174 (8%, 50 years). For power, a differential inflation rate of 2 percent was used for the first 15 years of the analysis, zero percent thereafter; replacement costs of facilities having lives less than 50 years were included.

Cost Component	Project A	Project B	Project C	Total
Present Worth				
Capital Costs ($1,000's)	$ 41,710	$ 32,110	$ 7,530	$ 81,350
O&M Costs ($1,000's)	62,130	50,360	12,520	125,010
Total Present Worth Cost	$ 103,840	$ 82,470	$ 20,050	$ 206,360
Equivalent Annual Cost[1] ($1,000/yr)	$ 8,490	$ 6,740	$ 1,640	$ 16,870
Incremental SWP Firm Yield (AF)	103,300	65,000	15,700	184,000
Unit Cost of Firm Yield (AF)	$ 82	$ 104	$ 104	$ 92

[1] Equivalent annual cost is based on a capital recovery factor of 0.08174 (8%, 50 years)

TABLE 5: Evaluated Expected Costs Using Present Worth Analysis over a 50-year Interval

CITY OF PHOENIX, ARIZONA

Of particular interest in the economics of artificial recharge is a comparison of the costs of surface spreading basins vs subsurface injection wells. Both have distinct advantages over the other in certain key elements, and the final result on relative economic cost can be very close. For example, basins are inexpensive to construct but require more land; injection wells eliminate evaporation losses but recharged water must usually be treated to drinking water standards. Consider the following example, which is based on a consultant's study in Phoenix, Arizona (Onyskow, 1985).

The City of Phoenix was interested in determining the cost of recharging 55,000 AF/year of flood water into an alluvial basin over twenty years. Cost were broken down into modeling and pilot study costs, design and construction costs, and the variable costs of water purchase, treatment and conditioning, and operation and maintenance. A breakdown and comparison of these costs is shown in Table 6. The costs are in 1984 dollars.

		Off-channel Basin	Injection Well
Modeling & Pilot Study		275,000	165,000 (1)
On-site testing		110,000	1,100,000 (2)
Design & Specs	(3)	100,000	110,000
Construction	(3)	3,800,000	5,600,000
Ancillary structures	(4)	175,000	0
Observation wells		275,000	0
Conveyance systems	(5)	1,100,000	0
Perimeter fence	(6)	165,000	0
Total Capital Cost (incl. modeling & pilot study)		$6,000,000	$6,975,000
Variable costs (per acre-foot, AF)			
Purchase water		53	53
Treatment		0	40
Conditioning		0	2
O & M		22	3
		$75/AF	$98/AF

NOTES

(1) injection well model study utilized existing wells
(2) includes 57 monitoring wells
(3) 15 No. 15 acre basins, 5 ft. deep
(4) ancillary structures include maintenance shop, yard and office
(5) land availability restrictions locate basins away from existing distribution system; all wells are near system
(6) well-fields either already have or require minimal fencing

Table 6: Costs: Surface Spreading Basins vs. Subsurface Injection Wells.

CITY OF TACOMA, WASHINGTON

The purpose of the two-source City of Tacoma project is to maintain an acceptable water quality year-round (See Facilities chapter). The primary source of water for the city is the Green River, which supplies high quality water for nine or ten months of the year. During the early spring, however, turbidity levels can become so high as to make the river water unacceptable. During this time six large pumps pull water from an aquifer. This water is blended with river water in order to bring the supply quality up to an acceptable standard.

In order to meet a growing demand, Tacoma had two basic options available: develop a new source of supply entirely separate to the Green River, or find a way of improving the quality of the Green's supply during the relatively short time of the year that it has unacceptable levels of turbidity. The latter option can be broken down into a) developing new treatment facilities to cope with the turbidity problem, or b) improving water quality at or near the river intake. All of the alternatives have the same objective -- that is, the same benefits. The NED plan is the minimum cost alternative.

The primary cost components of the new supply option depend on the nature of the new source. A surface water source would probably require investment in new storage, treatment and conveyance facilities. Secondary costs might include any of the components listed earlier in the chapter: e.g., environmental mitigation costs, utility and existing facility relocation costs, etc. Costs associated with the additional treatment option might include new investment in chemical mixing and flocculation tanks to coagulate and settle the suspended solids causing the turbidity problem. The capacity of the new facilities depends on the magnitude of the problem; for much of the year (i.e., for the ten months when there is no turbidity in the river), the extra treatment capacity would not be required.

The cost components of the river-aquifer system include: new abstraction wells, storage tank, transmission main from well-field to tank, blending valves and connections to the existing supply line. Turbidity sensors and automatic operations controls may also be components of both the treatment and groundwater pumping options. Water table decline causing increased pumping lifts and subsidence are examples of secondary costs of the conjunctive use option.

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PURPOSE OF FINANCIAL ANALYSIS

Financial analysis is an important element of project planning, and is closely related to traditional economic benefit analysis. Whereas national economic development (NED) analysis is approached differently for each of the various areas of water development activity (e.g., M&I supply, flood mitigation, hydropower, etc.), financial analysis is essentially the same for each area, including conjunctive use M&I projects.

As cost recovery is the basis of project financing, financial analysis focuses first on the cost recovery aspects of a proposed project, then on financing options. Fiscal impact analysis attempts to itemize the potential net fiscal benefits to be realized by prospective project sponsors. The benefits are expressed as changes in population and the associated changes in community revenues and expenditures that would be caused by the project. In conjunctive use projects involving more than one sponsor, fiscal impact analysis provides a basis by which project co-sponsors can share costs in accordance with their net fiscal benefits.

Cash flow analysis is a second method of financial analysis that focuses on direct revenues and expenditures. It tends to be somewhat more straightforward than fiscal impact analysis provided project outputs (water, in this case) can be realistically priced. In conjunctive use M&I water supply projects, cash flow analysis can be used to compare estimated costs (capital and O, M&R), to the necessary increase in water price and the appropriate price structure and cost recovery system. In projects that would involve multiple sponsors, each can undertake cash flow analysis to help determine its appropriate level of financial participation.

Once the method of cost recovery is established, a "funding package" can be assembled. The easiest funding package to

envision -- if not to secure -- consists of direct federal appropriations to the project. This is not, however, the way that the majority of conjunctive use projects will be funded. The principal financing decisions will be made by the project sponsor(s) at the state or local level.

There are two basic objectives the sponsors need to consider in assembling a funding package for any public works project: to structure the package so as to achieve the greatest funding latitude at least cost, and to maintain positive cash flow. An optimal capital structure provides the project sponsor with access to least-cost funding sources both before and after project implementation. The ideal financing package minimizes the project's immediate financial cost, maintains or enhances the sponsor's credit standing, and minimizes exposure to financial risks if conditions change.

Mugler, (1984) presents a comprehensive list of benefits that may be obtained through the careful structuring of a project funding package. All of the benefits are potentially applicable to conjunctive use projects. Mugler's list is reproduced below:

1) increased reliance on direct beneficiaries for cost recovery

2) diversified charging vehicles and revenue sources

3) enhanced capture of the consumer surplus in revenues

4) reduced risk to the sponsor of long-term revenue shortfalls

5) avoidance of pricing limitations

6) reduced revenue collection costs

7) increased access to funding sources to improve capital mix

8) reduced credit risk

9) reduced market risk to creditors

10) exploitation of tax and market niches

11) preserved or enhanced credit rating

12) enhanced financial flexibility

13) reduced financial transaction costs

14) reduced risk of negative cash flow in critical years

Before we leave this brief description of financial analysis, which is essentially performed for conjunctive use in the same way as for any other water supply project, a comment on one way in which the federal government could provide a useful service to a consortium of prospective conjunctive use sponsors should be made. The credit history, etc., of all sponsors must be considered, and a funding package that takes into account all the financing advantages and disadvantages of the individual organizations must be crafted. An extended financial analysis that might be undertaken by the federal government could typically investigate the following questions:

1) What organizations are the prospective sponsors (beneficiaries) of the proposed conjunctive use project? How does their purpose and function, institutional and political nature, legal and, especially, their financial constraints, etc., affect financial participation in the plan?

2) What is the capability of the prospective sponsors to participate in plan implementation? That is, what are the investment preferences, economic benefits from the proposed project, and especially, the financial condition (including credit history) and available financial resources, of each prospective sponsor?

3) What cost recovery options are available to each prospective sponsor? Specific questions might include: can budget surpluses be accumulated from year-to-year? is there a prohibition on transferring funds from dedicated revenue accounts (Government departments, etc.)? If yes, does the law need to be changed?, etc.

4) What are the financial advantages and disadvantages of each prospective sponsor? How does each contribute to the desirable features of the ideal funding package?

In addition, federal planners could assist an unsophisticated and financially-constrained sponsor to develop a feasible financing and cost recovery package. This could include an effort to reduce obstacles to, and induce support for, a plan which approximates the preferred federal plan, and resolve differences among the investment preferences of the federal government and the prospective sponsors.

FUNDING ORGANIZATIONS

Implementation of any water project, including conjunctive use, requires that a source of funds be obtained and that the funds be repaid according to a schedule. As outlined earlier, one source of funds has historically been the federal government.

In the absence of direct federal funding to specific water projects, state and local governments, and other local sponsors, will have to be the prime (financial) movers in implementing conjunctive use (Mugler, 1984).

Income from current revenues and the proceeds from assuming a debt obligation are primary sources of public works development funds for state and local governments. Current revenues consist mostly of taxes generated through sales, licensing, individual and corporate income and property assessments. The common form of debt obligation is incurred through the sale of bonds. Long-term, fixed premium bonds secured by general revenues have, until recent years, been the principal source of funds for financing state and local public works improvements.

In 1981-82, thirty-six states funded water development, at least in part, through direct appropriations from current (general) revenues (Rubin, 1984). Most such appropriations were small, averaging about $5 million each, and were usually used as seed money for local water projects. Although there are situations in which special state revenues have provided up-front capital, direct appropriations from general revenues may <u>not</u> be common in the future, and therefore should not automatically be considered to be available to fund conjunctive use development.

Conjunctive use water supply projects are just one of a list of public works activities that compete for financial support in an increasingly difficult funding environment. Close scrutiny is given to all development plans. When federal funding to states

is reduced more government services are often supported by local funding.

a. <u>Types of Funding Organizations</u>: A discussion of "funding packages," or "innovative financing," should include an identification of the state and local organizations that are involved in water resources development. Any member of the four organization types cited below is a potential sponsor of conjunctive use. Each is subject to different limitations (e.g., debt ceilings, the need to consider political consequences of actions, etc.):

1) General purpose units of government (and departments thereof). General purpose units may enter into agreements to conduct joint ventures or create special commissions which are delegated certain powers of the parties to the agreement.

2) Special districts, such as levee, drainage, soil conservation or sanitary districts, which are normally created by local referendum under procedures established by state law.

3) Independent authorities, districts and commissions created by special state legislation.

4) Investor-owned utilities or cooperatives which sell market outputs and which are usually regulated under state law.

Municipal departments and enterprise authorities which sell market outputs are together called "public utilities." There are two major differences between public utilities and investor-owned utilities. First, investor-owned utilities rely principally on investor equity for capital, whereas public utilities usually rely on debt. Second, public utilities are usually not regulated by state commissions and are operated on a cash basis; investor-owned utilities are usually regulated and are operated on a return-to-investment basis.

Compared to the water development activities of other sponsors, those of general purpose units of government have had relatively little financial independence. Faced with the task of assuring sufficient revenues are obtained without adverse political results for elected officials, general purpose government organizations have, in recent years, turned to a number of novel alternatives in order to create new borrowing authority. These include the creation of enterprise authorities and special districts, facility leasing and contracting for services, and the creation of municipally-owned utilities or the dedication of revenues to "revolving" or restricted use accounts.

b. Funding Constraints: Two factors may constrain a prospective sponsor's ability to optimize a mix of financing sources. First, the sponsor may not be authorized to use all funding sources. An investor-owned utility, for example, may be prohibited under regulations from generating "excess" revenues or from levying up-front charges to recoup capital costs. Second, the sponsor may be subject to legal limits on borrowing. Such limits vary from state-to-state. State departments, municipalities, and special districts may each be subject to a different set of limitations; in most cases, special districts are less encumbered than general purpose governments. Common limitations include:

1) Voter approval of new debt

2) Debt ceilings

3) Interest rate ceilings

4) Tax limitations

Table 7 shows the distribution of these legal limitations among states.

	LIMITS ON STATE GOVERNMENTS								LIMITS ON LOCAL GOVENMENTS								
STATE	Referendum required to create debt	Debt ceiling	Debt ceiling includes repayment contracts	Debt ceiling may be exceeded by referendum	Interest rate ceiling	Tax, revenue or expenditure limits	Ceiling on growth of revenues or expenditures	Limits on type of cost sharing	Referendum required for long term G.O. debt	Interest rate ceiling	Limit on property tax rate	Limit on property tax levy	Limit on general revenue	Limit on general expenditures	Limit on assessment increases	Limit on revenue or expenditure increases	Full disclosure prior to property tax increase
Alabama		X		X					X	X	X						
Alaska	X	X		X					X	X	X	X					
Arizona		X	X			X			X		X	X		X	X		X
Arkansas	X				X				X	X							
California		X		X	X		X		X	X	X			X	X	X	
Colorado		X					X		X		X	X					X
Connecticut																	
Delaware		X	X			X			X	X	X	X					
Florida					X				X	X	X	X					X
Georgia		X	X						X	X	X						X
Hawaii		X			X		X										X
Idaho		X		X	X	X			X	X	X	X			X		
Illinois	X				X	X			X	X	X						
Indiana		X									X	X					
Iowa		X	X		X			X	X	X	X	X		X	X		
Kansas		X	X	X				X	X	X	X	X		X			
Kentucky		X		X					X		X	X					X
Louisiana							X		X		X	X					
Maine		X		X	X				X								X
Maryland					X				X	X					X		X
Massachusetts								X			X	X		X		X	
Michigan		X			X		X	X	X	X	X	X					
Minnesota		X							X	X	X	X	X		X		
Mississippi		X			X				X	X	X	X					
Missouri		X		X		X		X	X	X	X		X				
Montana									X		X						X
Nebraska		X	X			X		X	X		X		X	X			
Nevada		X	X		X		X		X	X	X		X	X	X	X	
New Hampshire									X		X						
New Jersey		X		X			X					X		X			
New Mexico		X	X	X	X				X	X	X	X			X		
New York	X									X	X						
North Carolina								X	X		X						
North Dakota		X							X			X					
Ohio		X							X	X	X	X					
Oklahoma					X			X	X	X	X						
Oregon		X	X		X	X		X	X			X			X		
Pennsylvania		X	X	X					X		X						
Rhode Island		X	X	X	X	X			X	X							X
South Carolina		X			X	X			X	X		X					
South Dakota		X			X				X	X	X						
Tennessee					X	X	X			X							X
Texas		X	X		X		X	X	X	X	X						X
Utah		X				X		X	X		X	X				X	
Vermont					X				X								
Virginia	X							X	X								X
Washington		X		X		X		X			X	X	X				
West Virginia		X			X				X	X	X						
Wisconsin		X	X						X		X	X		X			
Wyoming		X			X				X	X	X						

TABLE 7: Constitutional and Statutory Limitations on State and Local Debt, Taxes and Expenditures (Mugler, 1984, pgs. 17, 18)

FINANCING TECHNIQUES

Long-term fixed premium bonds secured by general revenues have historically been the principal source of funds for financing state and local public works improvements; and investor equity has been the principal source for investor-owned utilities. However, high interest rates, voter and taxpayer sentiment and other factors have drastically altered the conditions under which most public works projects are financed. Conjunctive use water supply projects -- projects that now require 100% non-federal funding of their implementation and O&M costs -- are subject to these changed conditions.

About seven distinct groups of financing techniques for water projects have been identified (Mugler, 1984). The most important techniques available for conjunctive use financing are summarized in this section.

a. Bonding: The most common financing instruments for water projects have been debt instruments, including general obligation, revenue, assessment and dedicated tax bonds.

General Obligation (G. O.) bonds are tax-exempt municipal bonds that are fully guaranteed by the issuing authority. They must be approved by voters, and their aggregate sum is usually restricted to not exceed a given percentage of assessed valuation. All of the revenue sources of the sponsor contribute to meeting G. O. bond repayment obligations. If necessary, additional taxes or other revenues may be raised (by a sponsor with taxing powers) to service the debt if default becomes a possibility. This guarantee reduces the risk to the bondholder and enables the bond to sell at a lower interest rate than would otherwise be possible.

Revenue bonds are not fully guaranteed by the issuer and usually do not require voter approval. They may also be outside

the statutory debt limit of the issuing authority. Revenue bonds are payable from revenues received from project users, including M&I water sales. Generally, the interest rate on revenue bonds is about one-half of one per cent above the interest rate for G. O. bonds. There are a number of versions of the basic facility revenue bond: for example, "composite revenue bonds" use the revenues of an entire system, rather than a particular facility. Composite bonds are common for urban water supply systems, and may be particularly useful for conjunctive use financing.

A third type of bond is the <u>assessment bond</u>, which is best suited to small-scale developments. After a project is constructed, its cost is apportioned among the beneficiaries, each being billed according to the degree of benefit received from the project. The user may pay the full amount immediately or agree to the sale of an assessment bond with the user's property as collateral. The interest rate on special assessment bonds depends on such factors as the procedures for enforcing collection, the status of the assessment lien vis-a-vis other property liens and the financial penalty that may be imposed against delinquent beneficiaries. Assessment bonds are best suited to "collectively-consumed" project outputs that enhance property values, such as flood control projects. They are not particularly suitable for conjunctive use financing.

<u>Dedicated tax bonds</u> use a specific tax revenue source as security for debt. Examples of specific sources include excise taxes on goods that are complementary to use of common property resources. Motor fuel taxes and taxes on recreational equipment are examples. Not relying on general tax obligations, this type of bond usually carries a higher interest rate. A tax on water sales could provide repayment funds for conjunctive use dedicated tax bonds.

<u>Small denomination tax-exempt bonds</u> (so-called "mini-bonds") are designed to appeal to local investors and investors with

local funds. They are usually sold "over-the-counter." Grand River Dam Authority series 1983A bonds were sold in $500 denominations, with a limit per investor of $2,500 (Mugler, 1984). The Salt River Project, a major electric and water supply utility operating in metropolitan Phoenix, Arizona, sold $44 million worth of $500 denomination mini-bonds at an interest rate of 8.25 per cent in 1985-86. The bonds were mostly purchased by Arizona residents.

In 1970, General Obligation bonds accounted for approximately 65 per cent of bonded indebtedness; in 1983, the figure was under 30%. There are a number of reasons for this decline. They include an increase in the number of government districts and authorities with revenue bonding power, an increase in the number of "public purposes" that qualify for revenue bonding, a desire among officials to circumvent debt ceilings and voter approval, and a view that direct beneficiaries should pay for a facility. The trend away from G. O. bonds is likely to continue.

Finally, a note that the municipal bond market can undergo extremely volatile movements in interest rates (see Figure 20). As the financing cost of multi-million dollar bond issues can be greatly affected by just small movements in rates, the volatility has forced utilities and municipalities to forego the floating of a bond issue when interest rates climb to unacceptable levels.

b. <u>Up-front capital</u>: The use of available up-front capital is the optimal financing technique from the project sponsors' viewpoint. For a project cost of, say, $4 million dollars, the financing cost (of a bond issue, for example) at 6% interest over twenty years is approximately $3.3 million -- that is, a total of $7.3 million is repaid; at 12%, over $11 million is repaid. With 100% up-front capital, there is, of course, no financing cost.

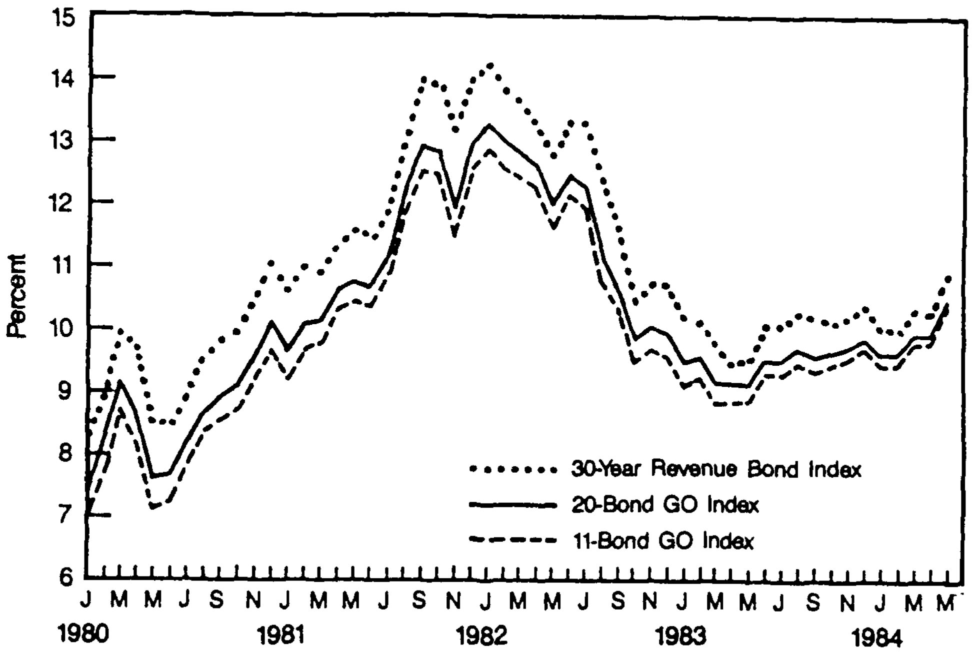

FIGURE 20: Municipal Bond Interest Rates: January, 1980 - May, 1984

Up-front financing implies the availability of surpluses, or the use of special assessments or system development (connection) charges. Surpluses are most likely to be available for projects that will become part of a system in which the major revenue sources are taxes and/or user charges. One-time assessments and connection charges tend to be unpopular with the owners of assessed properties and new customers, and are unlikely to be used as the principal source of funds for conjunctive use development.

It has been mentioned earlier that funding major water projects with 100% up-front capital from state and local funding sources is not common. However, it is possible that some relatively small-scale conjunctive use projects, or large projects developed in stages over time, could be completely financed in this way. This may be most likely in projects having more than one sponsor: surpluses held by at least some of the project sponsors could be pooled together to provide the necessary capital. However, surpluses may not always be available. An investor-owned utility may not have authority to collect "excess" revenues above those required for a "reasonable return," taxes, O&M, and depreciation reserves. Lack of authority, or budgetary or political pressure, may similarly constrain government units. Finally, financing sources may be used by governments to establish a (non-project specific) revolving account from which funds can be withdrawn as needed to provide up-front capital. The account is replenished from surplus general revenues, special fees and taxes, and possibly user fees from the completed project.

c. Leasing and contracts: In lease or contract financing, a private firm finances and owns a facility and either leases it to the public sponsor or enters into a contract to provide services to the sponsor. Advantages to the sponsor include a deferral of major expenditures, a preservation of financing capability, a possible reduction in cost due to tax advantages, and avoidance

of debt limitations. Leasing and contracts increase the revenue base without increasing debt, which enhances debt capacity. When properly structured, leasing and service contracts enable the private firm to obtain a desirable after-tax return on investment while the sponsor retains a source of capital.

There are other advantages to lease and contract financing. In addition to lower up-front cost to the sponsor, private financing of public facilities is advantageous to government sponsors with limited debt capacity, debt restrictions or limited access to capital markets (*). Also, the total implementation cost of a project is usually lower if private firms handle the design and construction work. Firms can usually perform the work more efficiently, mostly because they are subject to fewer set procedures and standards.

The tax implications of leasing should be carefully analyzed. The IRS has established a number of guidelines for characterizing a transaction as a lease (see (Mugler, 1984), pgs. 39-40). Table 8 shows the advantages of a 5 yr. depreciation for projects classified as personal property over regulated public utility projects which are currently subject to 15 yr. depreciation.

There are two basic types of lease agreement. First, true lease and its variants, finance lease and leveraged lease. Second, conditional sale lease (lease-purchase, or an "interim privatization" agreement). Detailed information on the exact characteristics of these agreements can be found in various sources (see, for example, pgs. 37-42 of (Mugler, 1984)).

(*) Some general purpose governments wanting to by-pass the restrictions that apply to general obligations may enter into lease agreements with special districts or authorities, which in turn take on the responsibility for bond issues.

Recovery Year	Recovery Percentage, 5-Year Property	Recovery Percentage, 15-Year Property
1	15	5
2	22	10
3	21	9
4	21	8
5	21	7
6	-	7
7	-	6
8	-	6
9	-	6
10	-	6
11	-	6
12	-	6
13	-	6
14	-	6
15	-	6

TABLE 8: Depreciation: Investment Recovery Under the Accelerated Cost Recovery System (Mugler, 1984, pg. 38)

The use of service contracts is often referred to as "privatization." The sponsor purchases the output or services of or financial interests in the facility, and gains no tax advantage. The facility owner (the vendor) has historically enjoyed full tax advantages, including accelerated depreciation and investment tax credit. Industrial development bond financing has also been used by the vendor with no loss of tax benefits. Privatization is one of the leading prospective methods for financing conjunctive use projects: "Leasing, conditional sales, and sale-leaseback are feasible financing techniques (for M&I water supply); however, use of service contracts is the technique which maximizes private responsibility and financing latitude "(Mugler, 1984, pg. 65). This may be especially true if governments encounter difficult economic times in the future.

d. Pricing: There is much controversy over the pricing of water outputs. It is true that many water supplies (e.g., water for irrigation of agricultural land) have historically been under-priced. Subsidies encouraged land development, but may have become too well-established. Subsidies of a somewhat different kind often exist in urban water supply systems where one of two pricing methods is usually used. Average-cost pricing sets the value of water at a level considered sufficient to recover historical (operating) costs. Marginal cost pricing reflects more accurately the cost of growth of a supply system: new consumers are charged according to the actual cost of providing their service. There can be problems in implementing marginal cost pricing, not the least of which are political in nature (Martin et al., 1984).

There are a number of pricing strategies that may be used independently or together in order to generate revenue efficiently. Two-part pricing consists of a fixed (or access) charge and a variable charge that varies with consumption; price discrimination varies the per unit price according to use (e.g., block rate pricing); peak pricing (or congestion tolls) charge

peak users a premium for water used at high demand periods - this tends to disperse use more evenly through time.

FINANCING WATER MANAGEMENT IN FLORIDA

Because water management problems in Florida transcend local political boundaries -- as they do in many areas -- the State has created a system of water management districts (WMD's) to fill what would otherwise be an institutional void between existing local and state environmental agencies (Webster & Morgan, 1983). Other regional authorities exist in Florida, but only the water management districts have the important powers of government: independent policy-making authority, enforceable regulatory authority, and taxing authority.

Ad valorem taxes -- taxes on real property -- are a major source of funding for Florida's five WMD's. Advantages of ad valorem taxes include:

1) The tax is relatively simple to implement.

2) Many of the benefits derived from water supply, flood and drainage control, etc., can be traced directly back to land and property owners.

3) The tax is easy to collect.

4) Large sums can be raised from nominal levies.

5) The State directly and indirectly benefits from the tax because of the overall similarity of special district and state water management goals.

The last two reasons are easily quantifiable: in FY84, Florida's five WMD's collected about $75 million in ad valorem revenue. If this revenue source were not available, funding would have come by direct appropriation from the State's general funds.

Two of the five WMD's were in place and operational at the time of the 1972 Florida Water Resources Act, which was an attempt to develop a comprehensive water planning and regulatory program, and became the foundation for the current water management system. These two districts already had taxing authority, and were expected to operate on a combination of ad valorem taxation and direct state funding. The three new management districts were expected to operate solely on direct state funding. However, it soon became clear that all districts needed a taxing authority in order to fulfill the scope of the 1972 Act.

A statewide referendum in 1976 sought and won the support of Florida residents to amend the state constitution to "authorize and limit local taxes for regional water management purposes." The success of the amendment, which affected the entire state, was heavily influenced by the geographic distribution of political power. Residents of southern counties, especially Dade County, had been paying for years to build and maintain water supply and flood control structures and did not perceive the proposition as a completely new tax.

Since 1976, all of the WMD's have levied ad valorem taxes and, indeed, the tax has become the primary source of income for all but the two smallest management districts located in the Florida panhandle. The other three districts -- all substantially larger that the panhandle districts -- have access to state funds, but have declined to seek grant-in-aid revenues. They claim administrative complications of seeking state support outweigh the benefits. How much revenue they may be turning down is unclear -- the law says that the functions of the WMD's "are of general benefit to all citizens and should therefore be 'substantially' funded from general revenue". No formula has ever been developed to quantify "substantial".

The critical variables in ad valorem taxation are the tax base (taxable assessed value) and the tax levy. There is wide variation in the tax base between the management districts ($2.3 billion to $127 billion in 1972). The wide range in assessed value means that some districts can raise large amounts of revenue with a nominal tax levy, while other districts generate a small amount of revenue with the same levy. Hence, the levies tend to be significantly higher in poorer areas. This causes problems inasmuch as taxpayers find the difference in assessments disturbing: all the districts have, in a general sense, implemented similar services and regulations and could, therefore, be expected to be close in their taxing patterns. One way to overcome the problem is to adjust boundaries so that poorer districts can take some or all of adjacent high tax base counties currently in neighboring management districts. This move would ignore the hydrologic boundaries that were used to define the WMD's in the first place.

Legal challenges to the use of ad valorem financing for water management in Florida have so far been unsuccessful. Most challenges have centered around the provision in the Florida Constitution that forbids ad valorem taxation on real property for state purposes. Although the WMDs functions usually relate closely to state water policy, the benefits of the districts are considered to be local in nature.

The water districts enjoy considerable power, not the least of which is the fact that appointed, not elected, officials decide taxing and spending policies. There is no direct legislative control over the expenditure of ad valorem taxes. Each district is directed by a nine person governing board appointed to a four-year term by the Governor and confirmed by the state Senate. The autonomy of the districts has been criticized by the legislature and some members of the general public. Indeed, the most vulnerable aspect of water management

by ad valorem taxation is possibly a simple "taxpayers revolt". However, good public relations should keep this threat at bay.

The water management districts in Florida have been successful, and the long-range outlook is for them to assume more responsibility, with a possible expansion into the areas of land use planning and regulation.

PRIVATE SECTOR FINANCING

Privatization has important advantages. It means that public works operations can take advantage of lower cost private development of a traditional public service, and at the same time, demand and get guaranteed performance. For industry, privatization is seen as an attractive long-term business opportunity; moreover, the investment banking community is eager to provide attractive funding methods, including the use of low-cost tax exempt debt, which helps keep service costs to consumers to a minimum (Reilly, 1985; Godfrey, 1986).

In many ways, industry financing of water-related projects can be a natural extension of areas of activity in which they have considerable experience. Every day industry tackles structural projects that are similar to much of the necessary infrastructure of water supply: for example, the design and construction of sophisticated facilities that process materials, and the 24-hour operation of these facilities. Private industry also understands the pressure of meeting tough budgetary and performance requirements, and the business (financial) risks associated with them.

The nation's first privatized municipal wastewater treatment and water treatment plants are located in Chandler, Arizona and Scottsdale, Arizona respectively. Chandler chose privatization for a number of reasons: it was seen as a way of preserving its bonding capacity for other needs, as a way of quickly meeting the demands of its rapid growth, and as an effective way of reducing its overall financing costs. The Chandler plant is designed for expansion from an initial capacity of 5 mgd to an ultimate capacity of 20 mgd.

The Scottsdale facility -- a 27 mgd, $28 million plant to treat water from the Central Arizona Project -- is being funded from two sources: from an initial sale of $25 million in tax-

exempt industrial development bonds, and with tax-exempt short term notes that carry a 4% interest rate. The short-term notes are particularly advantageous to the City: the rate for long-term tax exempt revenue bonds (normally used to finance a public project in Arizona) was 9.5% in December 1984 when the bonds were sold.

A limited partnership composed of Camp, Dresser & McKee, and a local development company, have contracted with the city to design, build and operate the plant for its first 23 years. Privatization does not change the status of Scottsdale's water operation, which remains a public utility: the city owns the water, the distribution network, and collects user fees. The bill that the partnership sends the city is based on agreed terms relating to operating costs and return-on-investment.

New water legislation, especially the 1980 Groundwater Management Act, is encouraging privatization in Arizona. In Scottsdale, a wealthy community, many new residential developments are being built around lakes and golf courses. The city has been reluctant to enter into long-term commitments to provide the domestic water required for irrigation, and developers are encouraged to provide their own wastewater reclamation plant for an assured lakes and irrigation water supply. In one agreement, Markland Properties Inc. built a $4 million, 1.7 mgd plant that provides an effluent that exceeds Arizona's reclaimed water standards (Hardt, 1986). The plant was turned over to the city upon completion and is being operated through a contract with a private company, Envirotech Operating Services Inc. The developer is recovering the cost of the plant through user fees; that is, through the sale of homes that adjoin the golf course. The homes are selling in the range $200,000 - $500,000 and higher.

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EFFECTS OF FACILITIES

Development of surface water supplies often involves structures and facilities for 1) storage, 2) diversion, 3) conveyance and distribution, and 4) reclamation and reuse. Apart from beneficial or detrimental local effects during construction of these facilities (e.g. employment, noise, traffic, energy consumption, air pollution), possible effects of the completed facilities on environmental values are discussed below.

a. Storage: Storage of water in multipurpose off-farm reservoirs not only enables timely release of water to meet irrigation and urban requirements, but also provides the storage capacity needed for augmentation of low stream flows to maintain desired water quality (Law and Skogerboe, 1972; Zuckerman, 1979).

Hagan and Roberts (1972), Jackson (1977), and Willey (1980) describe some of the adverse environmental effects associated with large storage reservoirs, including the flooding of scenic areas thereby affecting their previous recreational, fishery and wildlife values. In some areas there is a correlation between water storage in deep surface reservoirs and seismic activity occurring after the reservoirs are filled.

The formation of artificial lakes from storage reservoirs, however, can provide new waterfowl, fishing, and recreational values. Schamberger (1978) described efforts to evaluate such changes in habitat quality and quantity using "Habitat Units" to quantify fish and wildlife values. The damming of coastal streams for water storage and diversion can result in less sand deposition for renewing the recreational value of beaches (Univ. of Calif., 1970). Many believe that there would be less need for expensive and environmentally detrimental water storage and diversion structures on "wild and scenic rivers" if conservation practices resulted in lesser water demands or if, through good

conjunctive management, there were greater storage of surplus flows in subsurface, rather than surface, reservoirs.

Some of the nation's outstanding water storage and development projects have proved environmentally and economically detrimental in terms of the natural resource and income that have been lost through fishery declines. For example, in California's Sacramento-San Joaquin River system 96% of salmon habitat and over 65% of salmon production have been lost (Sacramento Bee, 1986). Similarly, it is estimated that salmon and steelhead production in that state's north coastal Trinity River system has dropped 75-80% over the past half century due to warmer water, lower flows, siltation, and stream blockage caused partly by on-stream water storage construction projects and partly by logging practices.

On-farm storage of water in ponds, as described by Henry and Gambell (1980) in a symposium on "Surface Water Improvements," provides both recreational and aesthetic amenities. Storage of water in deep surface reservoirs, such as Lake Shasta in northern California, produces cold water release from deep layers enabling cool stream water temperatures that favor fish species such as trout. At Oroville Dam (California), water can be drawn from different layers to provide better regulation of the temperature of water discharged downstream. McAfee (1980) points out that as water is used from surface reservoirs, the drawdown can have varying effects on aquatic life, depending on the characteristics of the reservoirs and on the rate and timing of drawdown.

The flooding of rice fields provides a form of off-stream water storage (Turner, 1978). The release of that water from northern California rice fields in autumn provides some (about 5%) augmentation of Sacramento River flow, but also increases total dissolved solids (by about 17%), though the major effect on river water quality seems to be a large local increase in suspended matter (Tanji, 1979).

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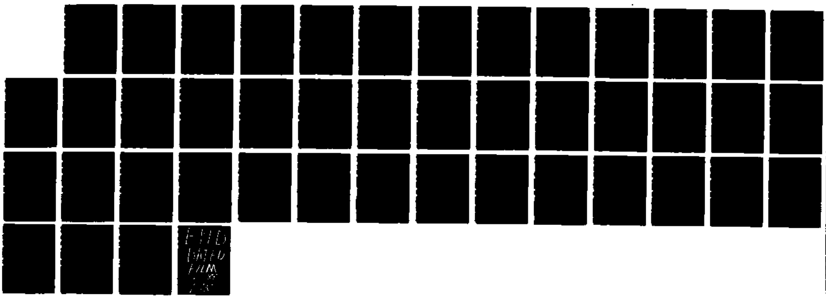

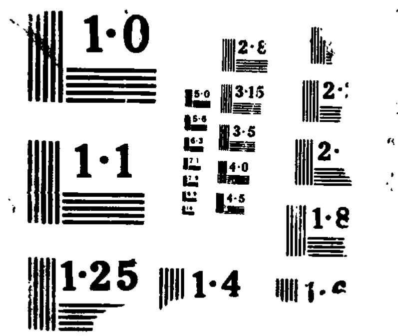
1·0
1·1
1·25
1·4
3·15
3·5
4·0
4·5
1·8

Although surface reservoirs have several on-site adverse environmental effects, they also provide many benefits, including flood control (Slogget, 1970), hydroelectric energy generation (Johnson, 1979), and recreation (Gale, 1979).

b. Diversion: Water diversion from a river or stream causes a reduction in flow with consequent effects on instream needs. ("Instream needs" include the water quantity and quality requirement for fish and other aquatic life, navigation, recreation, and aesthetic values). For example, Smith (1980) reported that the inadequate instream flows resulting from water diversions by the Trinity River Division of the Central Valley Project (CVP) in California led to a 90% decline in the anadromous fishery traditional to the Trinity River system. Murray (1980) reports that increasing releases to the ocean-bound flows of the Trinity system would (in addition to curtailed hydro-power production) reduce the inland-bound water yield of the CVP by 1-2 acre-feet for each acre-foot of reduced diversion. He also reports the findings of a consulting firm that the instream values of the Trinity cannot be restored simply by reducing water diversions, but must be accompanied by improvements in land use and fishery management in the Trinity basin. Graff (1980) went so far as to state that increased diversions of fresh water leading to the Sacramento-San Joaquin delta system are "a prescription for environmental disaster."

While instream flows can be increased by reducing diversions, they are also increased when return flows enter streams and rivers instead of being irrecoverably lost by evapotranspiration. Those return flows will have both quantity and quality effects (Woods and Orlob, 1963; Skogerboe, 1973; Bayer and Knight, 1976; Biggar et al., 1976; Tanji, 1979). On the other hand, if water is conserved for local use by reducing return flows to streams and rivers, some of these authors point out that there may be real benefits to instream values because of reduced degradation of stream water quality caused by sediment,

toxic chemicals, nutrients, and salts carried in the return flows. Reducing agricultural return flows to streams will prevent acute changes in aquatic life, such as macrobenthos (Kreis and Johnson, 1968) and periphyton (Halbach and Falter, 1974; Hayes et al., 1978).

c. Conveyance and distribution: Canals and ditches used to convey developed water usually have a minimal effect with regard to land excavation because of the narrow strips of land they occupy, relative to, say, a water storage reservoir. However, the linear extent of a water distribution system may be regarded by some to be a blight on the landscape. In some cases, however, canals and ditches provide a welcome relief to otherwise dry and monotonous terrain.

Seepage from unlined canals and ditches is known to be a source of water for riparian and wetland habitat for wildlife (Calif. Dept. of Water Resources, 1976; Interagency Task Force Report, 1979). Seepage from unlined ditches also provides breeding grounds for mosquitoes (Mitchell and Bohart, 1976). Mosquito breeding within the ditches can be discouraged by clearing aquatic weeds so as to maintain water flow (Mulla, 1980; Univ. of Calif., 1980).

While water transfers, e.g., through an agricultural water purchase plan, may enable more efficient utilization of water, it could also have beneficial or adverse effects on wildlife and fisheries in the environs of the water seller and of the water purchaser (Calif. Dept. of Water Resources 1979a).

Walker (1972) described the dangers of salinization of land adjacent to unlined canals in arid areas, particularly if the water has a relatively high salt content and the land is poorly drained.

In some areas maintenance of adequate amounts of good quality water in groundwater aquifers depends on recharge by seepage from canals. Conserving water and improving the efficiency of its conveyance by lining canals which convey good quality water would, therefore, result in a degradation of groundwater quality. On the other hand, in areas where irrigation canals and laterals convey water which is relatively high in salt, e.g., Colorado River water conveyed in the Imperial and Coachella Valleys, would result in less salt loading from the seepage water (Evans, 1970; Skogerboe and Walker, 1972; Walker et al., 1978). In the Grand Valley of Colorado, Evans et al. (1978) estimated that canal linings reduce salt loading at unit costs ranging from $190-700 per metric ton of salts removed. Seepage from canals and laterals contributed, respectively, 23% and 32% of the subsurface return flows and consequent salt loading in the Grand Valley area. Law and Skogerboe (1972) stated: "The economics of canal lining has been justified primarily on the basis of the value of water saved. The possibility that canal seepage may greatly increase the total contribution of dissolved solids to receiving waters has only recently been given serious attention."

d. Return flows and reuse: The final effects of water development projects are those associated with the return flows that they generate and with the reuse of those return flows. (Return flow is the portion of withdrawn water that is not consumed by evapotranspiration and returns instead to the stream or aquifer from which it came or to another body of water.) The environmental effects are largely related to degradation in the quality of water with each successive reuse.

Some of those effects, e.g., percolation of nutrients, pesticides and other toxic materials to receiving waters, were described earlier. In "A Guide to Information Sources of Water Pollution", Knight and Simmons (1980) compiled a useful bibliography that included references on effects of irrigation

practices on stream water quality. It is important to remember that the effects 1) vary with site and biologic species; and 2) may occur relatively soon or could be insidiously slow in developing. For example, osmotic effects of saline drainage waters may be manifested within days or weeks, but potentially toxic compounds in drainage water may take decades to move to, and accumulate at toxic levels in, receiving waters.

Reuse of return flows is an inherent part of any water project, particularly in areas where scarcity of the prime water source necessitates reuse, despite quality degradation. Reuse may be 1) intentional, e.g., use of treated municipal wastewater; or 2) unintentional, e.g., diversion of streamwater downstream from a point where return flows have drained into it. Regardless of whether reuse is intentional or incidental, the quality of the water is bound to have some degree of short- or long-term effect on plant, animal or human life.

It should also be kept in mind that some of the water draining from mainly agricultural areas served by water projects contributes to riparian vegetation along canals, ditches and drains and to wetland/marsh vegetation, all of which provide wildlife habitat, including cover, feed, shade, and travel avenues. For example, the California State Department of Fish and Game identified over 2,000 miles (or roughly 5,000 acres) of strip riparian vegetation in the San Joaquin Valley and more than 50,000 acres of riparian vegetation on other areas, primarily supported by agricultural water supplies and return flows. In addition, there are about 25,000 acres of private and public wildlife management areas which are supported by agricultural return flows in the San Joaquin Valley. Thus, wildlife habitat supported by agricultural water supplies in the Valley totals an estimated 80,000 acres.

It is widely believed that the present area of wildlife habitat in many parts of the country is far from adequate,

considering the vast areas lost to development since the turn of the century. Reductions in conveyance system seepage and agricultural return flows would, therefore, adversely affect the distribution and the area of already depleted wildlife habitat. Curtailments of the return flows which sustain that vegetation would necessitate costly new diversions and pumping of water if wildlife species are to be sustained.

For more data on reuse of water in California, see Calif. Dept. of Water Resources (1983) and Davenport and Hagan (1985).

EFFECTS OF APPLICATION OF WATER

One of the major purposes of developing water is to meet agricultural, municipal and industrial demands. The application of water for these uses, however, can affect environmental values in several ways, as described below.

In California, over 85% of applied water goes to agriculture, primarily for irrigation. Jackson (1977) described how irrigation is perceived by farmers and by non-farmers to cause environmental damage, and listed the types of on-farm and off-farm damage associated with irrigation. Farm oriented damage included: increased alkalinity and salinity; erosion; creation of gullies; waterlogging of soils; and spread of weeds. Canyon oriented damage included: destruction or degradation of scenic qualities in canyons and mountains; destruction and/or deterioration of fishing or streams; deterioration of water quality in streams; and flooding of scenic areas. Walker and Skogerboe (1980) described optimal river basin solutions to alleviate environmental effects resulting from irrigated agriculture.

One of the major effects of irrigation in arid and semi-arid areas is the long-term salinization of soils when proper water management and drainage are not provided. There are strong interrelationships between salts in irrigation water, salts inherent in soils and their parent rocks, and salts in both surface and groundwaters that receive agricultural return flows.

Reduction of unnecessary runoff and deep percolation from farms, by an improvement in irrigation application efficiency, will generally reduce the total salt content of receiving surface and groundwaters (Law et al., 1970; Olson et al., 1973; King and Hanks, 1975; Huszar and Sabey, 1978; Pratt et al., 1979; Cooperative Extension, 1980). Bingham et al. (1971) studied a 960-acre citrus watershed and found that of the water entering

the watershed, 40-50% departed as effluent drainage. The nitrate concentration in the effluent was as high as 87 ppm, averaging 50-60 ppm. This nitrate loss (about 45% of the applied fertilizer nitrogen) could contribute to degradation in the quality of receiving waters. The authors note, however, that in the Imperial Valley of southern California, where much higher nitrogen applications are used, effluent waters are relatively free of nitrate because of its reduction to gaseous nitrogen in the vicinity of the water table or tile drain.

When irrigation systems, such as sprinkler and drip, are properly managed there can be reductions in both on-farm water demands and salt loading from irrigation return flows (Patterson and Wierenga, 1974; Kepler and Pitts, 1978; Walker et al., 1978). This is particularly true early in the irrigation season when there are larger accumulations of salts in the soil profile. Rauschkolb et al. (1979) emphasized that irrigation management techniques which lead to greater amounts of deep percolation may result in lower nitrate concentrations in the soil profile, but contribute to transfer of a greater total amount of N to receiving waters. If water is managed in a manner which improves the efficiency of utilization by crops, the nitrate concentration in the root zone may be high, but mass emission below the root zone would be low.

Information on groundwater contamination in ten states of the United States was reviewed by Pye and Patrick (1983). In California the most frequently reported sources of contamination were: 1) saltwater intrusion (resulting from overpumping of freshwater aquifers in and near coastal areas; 2) nitrates from agricultural practices; and 3) brines and other industrial and military wastes. Pye and Patrick point out that groundwater pollution sources are not easily observed, " ... nor are their effects seen until damage, which is often irreversible, has been done." "Prevention of groundwater contamination," they state, "is a more effective strategy than cure."

An unexpected effect of applying water from a large development project recently came to light in California's San Joaquin Valley. When irrigation was introduced to parts of the westside of the valley, selenium from marine deposits in the irrigated lands was carried in agricultural drainage waters to Kesterson Reservoir, the present terminous of the incomplete San Luis Drain. Since Kesterson also serves as a wildlife refuge, the selenium accumulating in mud, algae and aquatic plants, apparently resulted in toxicity and death of some wildlife species.

In one of a series of articles by Tom Harris, Jim Morris and Michael Williamson, the Sacramento Bee (1985a) stated: "Selenium, the lethal natural poison that has killed and deformed birds, fish and other wildlife in the San Joaquin Valley, is poisoning wildlife, livestock and even some rural families over thousands of square miles in 15 Western states. ... At fault, in most cases, are massive federal water projects. Built to make the parched West bloom through intensive irrigation, scores of these projects are robbing waterfowl and wildlife habitat of limited fresh water and returning it laced with selenium - and other toxicants - to taint wildlife refuge areas, lakes, rivers and reservoirs used for drinking water, irrigation or recreation."

Another article in the Bee series on selenium (Sacramento Bee 1985b) stated: "Dating back nearly 100 years were a series of reports on the potent toxicity - and proliferation- of selenium throughout the West, centered in the Rocky Mountain belt but extending to the Plains states of the Dakotas, Nebraska and Kansas, and beyond." The subtitle of that article suggests that "studying (the) past may have prevented (the) poisoned present," reminding one of the adage: "The only thing we learn from history is that we don't learn from history." It should be noted that while the Sacramento Bee articles on selenium served to focus attention on the ever-present potential for toxicity

problems due directly or indirectly to human activities, concern has been expressed by some regarding the scientific accuracy of portions of the articles.

One should not conclude that because water development and irrigation projects in arid areas have historically led to problems with salinity and toxicity from specific elements (selenium is not the only problem element), such projects should never, therefore, have been developed, regardless of their relatively short-term economic benefits. It should lead professionals, through accumulation and use of information, to 1) anticipate potential problems associated with water projects; 2) develop management strategies to monitor and overcome them; and 3) legislate funding for that management as a part and parcel of the whole project. For example, there are those who believe that on the westside of the San Joaquin Valley, much of the environmental damage manifested as selenium toxicity in the Kesterson pond area might have been prevented (or greatly minimized) if the San Luis Drain had been completed (as originally planned, but not funded) with an outlet to the delta or bay. The Kesterson ponds were to be used only as regulating reservoirs. Instead, the drain terminated in the Kesterson ponds which, because they had no outlet other than evaporation and some seepage, became an increasingly concentrated reservoir for toxic wastes.

The question still remains as to how much environmental damage would have occurred in the delta/bay areas if the San Luis Drain had exited there. In all probability, although some degree of water quality degradation is unavoidable, the damage would not have been as concentrated as in the Kesterson area because drainage outflows would be continuous and, with the help of regulating reservoirs, the drain discharges could have been timed to coincide with high rates of river outflow through the delta to ensure dilution and flushing of toxicants.

Along with the quality consequences of applying water from surface water projects, there are quantity aspects which have direct or indirect environmental effects. During early irrigated agricultural development, the application of surface waters tended to undesirably raise groundwater levels. Today, however, the combination of large-scale stream diversion and groundwater pumping have generally resulted in a steady lowering of groundwater levels in many aquifers, in spite of a certain amount of replenishment from local irrigation and from groundwater recharge projects (in areas where local geology and hydraulics permit).

The introduction of a surface water supply to an area that increasingly relied on groundwater pumping (sometimes to the point of overdrafting an aquifer) could cause a rise in the water table because 1) surface water substitutes for all or part of the groundwater supply, and/or 2) deep percolation of excessively applied surface water recharges and raises the water table. For example, the Arvin-Edison Water Storage District (1983) had problems of groundwater overdraft (about 200,000 acre-feet per year prior to importing Central Valley Project water in 1966) and pumping lifts of over 600 feet in some areas. The average groundwater depth in the district was lowered by pumping from 280 feet in 1956 to 380 feet in 1966. Without the importation of surface water and the District's conjunctive use program, it is estimated that by 1983 the average groundwater level would have dropped below 500 feet. Instead, it leveled off at about 300 to 390 feet between 1966 and 1978, and rose to 375 feet between 1978 and 1983. This not only reduced pumping depths and associated energy costs to those farmers in the District who still rely on groundwater, but also substantially reduced subsurface inflow from neighboring areas and improved the quality of water by preventing subsurface inflow of boron to the District's pumped aquifers.

The application of irrigation water transferred from water storage projects to arid and semi-arid areas also changes the local climate and micro-climates of those areas due to the transfer of water vapor by evapotranspiration to the air. Thus some radiant energy, which would otherwise be used to heat the air in dry areas, is used to vaporize the introduced water, resulting in lower air temperatures and higher humidities (DeVries, 1959; Davenport and Hudson, 1967).

The introduction of irrigation also affects air quality in other ways. For example, agricultural burning of straw and stubble from irrigated cereals causes some air pollution problems despite regulations prohibiting burning on meteorologically unfavorable days (Osterli and McNelly, 1968; Fritzell, 1975; Greene, 1979).

EFFECTS OF GROUNDWATER PUMPING

The major environmental effects of pumping from aquifers, as a source of water, stem from continued overdraft of groundwater supplies. These effects include: 1) land subsidence as subsurface deposits compress and consequent loss of aquifer storage capacity; 2) saltwater intrusion in coastal areas; 3) invasion of poorer quality groundwater in inland aquifers; 4) cessation of natural spring flows; and 5) greater energy requirements and therefore more rapid use of fossil fuels and consequently greater air pollution.

Kelly (1980) points to several cases where groundwater withdrawals have affected streams and ponds, leading to efforts to limit pumping. Use of shallower unconfined subsurface water may result in the drying up of marshy areas and the wildlife habitat they provide, and natural phreatophytic vegetation may die if its roots are no longer supplied by a subsurface water table.

Describing the effects of subsidence caused by groundwater overdrafting in California, Howard (1982) wrote: "Widespread subsidence in the San Joaquin Valley has reached as much as thirty feet in some places and has required modification of canals to maintain the slope necessary to transport water. Near San Jose, levees have been raised many times to hold back waters of San Francisco Bay. Saline water has entered depleted fresh-water aquifers in Orange County, the coastal plain of Los Angeles, near Oxnard in Ventura County, in the Salinas Valley, in the Pajaro-Santa Cruz area, and in Napa and Sonoma valleys at the north end of San Francisco Bay."

A report by the U.S. Geological Survey (Ireland et al., 1982), while pointing out that in California's San Joaquin Valley land subsidence due to groundwater overdraft began in the mid-1920s, states that this subsidence " ... probably represents

history's greatest single manmade alteration in the configuration of the Earth's surface." Subsidence continued in the Valley until surface water was imported in the 1950s and 1960s.

AIR QUALITY, NOISE, SEISMICITY

During construction of storage, transfer and recharge facilities for conjunctive use projects there might be an increase in air pollution because of exhaust from construction equipment and increased traffic around the site. This would be a temporary effect.

Ponding of water in groundwater recharge areas for long periods in summer, when conditions are conducive to algal growth, may result in objectionable odors, particularly to downwind sites. Odors from recharge ponds are more likely to occur when reclaimed wastewater is used.

The current (pre-project baseline) level of air pollutants for the site area could be obtained from the Air Resources Control Board, bearing in mind that pollution levels may vary with time of day and season. The presence of objectionable odors in the air could be determined simply by local inquiry. A useful up-to-date test providing detailed information on air quality and the effects of air pollutants has been prepared by Godish (1985). In most cases, conjunctive use projects are not expected to produce long-term deterioration in air quality.

During the construction phase of setting up new facilities, or renovating old ones, for conjunctive use, an increase in noise levels is inevitable because of heavy construction equipment and increased traffic in the area. Some equipment raises noise levels to 75-100 dBA at 50-foot distance. After the construction phase, noise levels are likely to be limited to the whir of pumps, but that can be muffled by insulated housing and by subsurface installation.

There is some concern that changes in groundwater storage due to artificial recharge could affect the probability of earthquake occurrence. However, the presence and fluctuation of

groundwater is only one of many factors which might influence the transmission of seismic waves. Damage is more likely to occur because earthquake motions are modified as they pass through heterogeneous strata (e.g., bedrock to alluvial deposits) than by the presence or absence of groundwater in the deposits, although the level of groundwater could affect the degree of damage.

ENERGY CONSUMPTION AND GENERATION

The basis for including energy as a category of environmental effect due to conjunctive use, is that any expenditure of energy could involve consumption of non-renewable fossil fuel resources with consequent contributions to air pollution. Conversely, a net saving of energy would result in the opposite effects. In most instances a large energy demand for conjunctive use occurs in mid- to late summer to recover water stored in aquifers. Since this is also the time when the storage head in surface reservoirs is low, hydropower generation is less likely to be the energy source for groundwater pumping than is a fossil fuel source. Also, since hydropower is already nearly fully allocated (because it is relatively cheap and cleaner than synfuels), new conjunctive use projects, which would be making additional demands on the total energy system, would probably have to rely on fossil fuels, which are environmentally more detrimental than hydropower.

It is possible that new conjunctive use projects could generate some electric power if new canals for transporting water have down-hill gradients sufficient to justify installation of mini-hydropower units. Increasing costs and pollution hazards of other power sources (synfuel and nuclear) might justify installation of such units in existing and new canals required for transporting conjunctively used water. A conjunctive use project may also be regarded as a short-term energy saver in the sense that utilization of "naturally constructed" aquifer storage space reduces to some degree the need to expend energy for materials and construction of surface reservoirs. That, however, means that the long-term potential for hydropower production from surface reservoirs (if suitable sites are available) is foregone. Another form of energy savings occurs when recharging deep aquifers with surface water raises the water table and thereby reduces pumping depths. Some energy saving also occurs because conjunctive use usually increases total water storage capacity in

the state, thereby reducing the need to expend energy to overdraft aquifers in order to meet all of the water requirements. For some areas conjunctive use occurs because surface water is delivered in lieu of pumping groundwater, thus reducing pumping energy in those areas.

In most cases, however, a conjunctive use project is regarded as a net consumer of energy because power may be required to: 1) transfer surface water uphill to some recharge sites; 2) construct distribution, storage and recharge facilities; 3) enable recharge by pressurized injection wells; and 4) pump to recapture water from subsurface storage. An example of an energy balance sheet for a groundwater storage program using a theoretical model for California's San Fernando Basin is described by the California Department of Water Resources (1979b). In one example, the Department calculates energy costs (in billion BTUs) at 28,030, compared with energy benefits (from reduced groundwater pumping and reduced pumping lifts) of only 2,410, resulting in a net energy cost of 25,620.

HEALTH AND SOCIAL ASPECTS

This category of environmental effect is, for obvious reasons, of primary importance to us and, in fact, all of the effects discussed in this chapter have some direct or indirect bearing on the quality of human life.

a. Health and hazards: Apart from the relatively minor air pollution effects already described, the major risk to human health resulting from conjunctive use occurs when recharge water of poor quality reaches aquifers which are a source of water for drinking or for irrigating certain food crops. That can occur 1) when degraded water is used for recharge, and/or 2) when recharge water picks up hazardous pollutants already in the soil profile en route to a groundwater source.

Criteria and regulations have been developed to assure public health protection when reclaimed wastewater is used for irrigation, impoundments, and groundwater recharge (e.g., Calif. Dept. of Health Services, 1978). These include water-quality standards, treatment process requirements, sampling and analysis requirements, operational requirements, and treatment reliability requirements. In the California Administrative Code Title 22 Division 4 on Environmental Health, Chapter 3 describes Reclamation Criteria, and Article 5.1, section 60320 on Groundwater Recharge states, in part: "Reclaimed water used for groundwater recharge of domestic water supply aquifers by the surface spreading shall be at all times of a quality that fully protects public health. ... recommendations will be based on all relevant aspects of each project, including the following factors: treatment provided; effluent quality and quantity; spreading area operations; soil characteristics; hydrogeology; residence time; and distance to withdrawal." Primary drinking water standards for inorganic and organic constituents are given in the Administrative Code.

The Environmental Protection Agency's Office of Drinking Water has issued nonregulatory advisories for 52 contaminants, including information on health effects, analytical methodology and treatment technology. Copies are available from: Office of Drinking Water, Health Advisories Manager, Rm. 1011 East Tower, 401 M St., SW, Washington D.C. 20406.

Health aspects of groundwater recharge are described quite thoroughly by Nellor et al. (1985), using the Montebello Forebay groundwater recharge facilities in southern California as an example. Included in the study is information on: 1) water quality characterization of groundwater, reclaimed water, and other recharge sources in terms of their microbiological and inorganic chemical content; 2) toxicologic and chemical studies of groundwater, reclaimed water, and other recharge sources to isolate and identify health-significant organic constituents; 3) percolation studies to evaluate the efficacy of soil in attenuating inorganic and organic chemicals in reclaimed water; 4) hydrogeologic studies to determine the movement of reclaimed water through groundwater and the relative contribution of reclaimed water to municipal water supplies; and 5) epidemiologic studies of populations ingesting reclaimed water to determine if their health characteristics differ significantly from a demographically similar control population.

Readers may also find the following references useful in assessing the health aspects of water associated with conjunctive use projects: Baird et al.(1980); Calif. State Water Resources Control Board (1976); Cheh and Carlson (1981); Crook (1978); Greenberg et al.(1980); National Interim Primary Drinking Water Regulations (1979); Roberts et al. (1982); Tomson et al.(1981); More recently, Rice (1985) edited a book for the Drinking Water Research Foundation which includes chapters on monitoring and analysis and on groundwater contamination.

Another type of health risk associated with impounding water for storage or recharge is the propagation of mosquitoes, midges and other troublesome insects. Conjunctive use facilities may also become potential drowning hazards unless properly fenced and posted with warning notices. In fact, all groundwater recharge operations have provisions to exclude the public from the recharge area.

On a more positive note, since the purpose of conjunctively managing surface and groundwater supplies is to improve overall efficiency of storage and availability of water resources, water becomes more available to more areas in drought years. This prevents, or at least reduces, health and safety risks and environmental damage associated with unexpected or otherwise unprepared-for water shortages. Groundwater is particularly useful in compensating for the long-term year-to-year variation in surface water supply. Were it not for groundwater reserves, droughts would often have more severe effects on economies and environments because remaining surface supplies needed for human and environmental requirements would be even further depleted. However, reliance on groundwater reserves in a few lean years should not lead to complacency because parts of the nation still face the possibility of severe long-term droughts (many consecutive years of low precipitation). Conjunctive management, on a long-term basis, of surface and subsurface storage reservoirs, would reduce the risks of economic and environmental damage from prolonged drought.

In today's artificial hydrologic system of channels and levees, flood damage occasionally occurs when watershed runoff temporarily exceeds the capacity of rivers, channels and surface reservoirs to accommodate flood flows. Conjunctive management of surface and subsurface reservoirs, along with improved weather forecasting, would increase total storage capacity, and thus reduce the risk of flooding, by transferring surface water to

aquifers. That would then allow a greater safety margin for accommodating flood runoff in surface reservoirs.

Nevertheless, although the benefits to be gained by groundwater recharge may be great in terms of total volume of water reused, the costs could be even greater if the recharge projects render the groundwater unfit for use. (See item 8 later in this paper for effects on water quality.)

b. Population: The increased yield of water resulting from efficient conjunctive use can help in meeting present deficits and projected demands for water by agricultural, municipal and industrial users. However, there are those who believe that increasing the availability of water in naturally water-deficient areas causes expansion of population and urbanization in those areas, resulting in various adverse consequences to the environment associated with rapid urbanization, a la the Los Angeles metropolitan area. Those consequences include air and water pollution, loss of wildlife habitat and agricultural land, and further demands on energy and water resources.

c. Recreation and aesthetics: When conjunctive use requirements necessitate new diversions of water from streams to groundwater recharge ponds or to provide surface water in lieu of groundwater pumping, streamflows may be reduced to the extent that recreational activities could be affected, at least during some part of the year when flows are already low.

In sites where recharge spreading basins are a year-round operation, it may be possible to develop recreational facilities for fishing, picnicing, birdwatching and photography.

d. Cultural: Conjunctive use projects, particularly development of new recharge areas, could possibly disrupt historic or archeologic sites. Inquiries to local historic

societies could prevent such disruption and would undoubtedly be appreciated by all concerned.

LAND AND VEGETATION

New conjunctive use projects may affect land at the surface as well as in the subsurface profile. However, when groundwater recharge can be accomplished with existing spreading grounds and well fields, no additional land is needed.

a. Surface: Construction of new groundwater recharge facilities (including spreading basins, injection-extraction wells, connecting pipelines, etc.) may require some land leveling and embankment construction, thereby somewhat altering local topography and exposing land to the possibility of erosion. In some cases, old recharge ponds which are clogged with debris and silt (usually in the top few inches) must be cleaned and rehabilitated to enable continued recharge of aquifers. This beneficially improves infiltration of the land surface. Separate treatment and settling ponds may be required to prevent clogging of basins recharged with poor quality water.

New conjunctive use facilities for water storage, treatment, transport, and recharge may affect land use planning, unless rights of way already exist for the facilities.

b. Subsurface: The major factors affecting land subsurface are problems associated with rising water tables and soil salinity. In some cases artificial recharge of groundwater in combination with natural recharge in wet years may raise water tables and cause various water logging problems associated with saturated soil profiles.

In arid areas, high water tables usually lead to a net upward migration of salts already present in the soil and water, with eventual salinization of the soil surface and soil profile above the zone of saturation, unless periodic leaching and drainage are provided. When high quality surface water is imported to an area for irrigation in lieu of pumping relatively

saline (but usable) groundwater, further salinization of the soil would be stopped and salts could be leached below the root zone with the better quality surface water.

In areas where land subsidence continues due to groundwater overdraft, a conjunctive use project which brings in surface water for recharge, and/or use in lieu of groundwater pumping, would prevent further loss of aquifer storage space caused by subsidence. Ireland et al.(1982) suggest continued monitoring using extensometers, water-level recorders and periodic releveling in subsidence-prone areas.

Since conjunctive use involves redistribution of water and consequent changes in water table levels, there is bound to be some effect on vegetative species that tap the water table (phreatophytes). For example, stream water diversion lowers the level of water in the stream bed and thereby affects riparian and phreatophytic vegetation adjacent to, and on the flood plain of, the stream. In parts of the western United States vegetative species (e.g., saltgrass, greasewood, saltcedar, cottonwood, willow, baccharis and mesquite) have become established because of the presence of riparian flows and their connected water tables. The dominance of a particular plant species depends not only on climatic and salinity factors of the area, but also on water table depth and fluctuations. In fact, lowering of the water table was at one time suggested as a means of eradicating troublesome water consuming vegetation species. Thus, any transfer of water from one location to another to enable conjunctive use could affect phreatophytic species in both locations by making moisture from the water table less or more available to the root systems.

Development of groundwater recharge ponds promotes vegetative growth around their perimeters. Whether or not such vegetation is eradicated depends on costs, hazards of using

herbicides near recharge areas, and the aesthetic and wildlife benefits of the vegetation.

WATER QUALITY

This is perhaps the most important long-term environmental factor that could be affected by conjunctive use. Both surface and subsurface waters are affected because surface water is used to recharge groundwater and part of the pumped groundwater is often diverted to streams as return flow after useage.

a. Surface waters: Diversion of surface water for groundwater recharge or for use in lieu of groundwater pumping deprives streams of part of their flow that could serve to dilute salts and other pollutants which enter the river at points downstream of the diversion point. The severity of the effect on stream water quality would, of course, depend on the original quality of the water and on the size of the diversion relative to the size of streamflow. Canter (1985) provides an excellent practical guide to plan and conduct river water quality studies that are needed to establish baseline conditions, set water quality criteria and standards, monitor temporal change, and determine effects of specific projects and developments.

b. Subsurface waters: As already pointed out, recharge of groundwater can sometimes raise water tables so that salts which may be inherent in the upper soil profile dissolve and contribute to degradation of the subsurface water. On the other hand, some aquifers have become so depleted that relatively poorer quality water from neighboring groundwater basins (or from the ocean in coastal areas) may enter and gradually degrade the quality of the aquifer. In such cases, recharge of the aquifer would raise its hydraulic gradient to prevent further degradation and, depending on the amount and quality of recharge, may improve the quality of the neighboring inland aquifers. The problems of inland and coastal salt water intrusion into groundwater have been described in a recent book by Atkinson et al.(1985). Recharge of salinized coastal aquifers with fresh water does not create an abrupt interface between the two fluids. Since they are miscible there

is a transition zone of a few meters to several hundred meters depending on aquifer characteristics and tides. Revell (1941) described chemical criteria for determining intrusion of seawater into groundwaters.

When relatively high quality water (e.g., 100 mg/l TDS) is imported to recharge an aquifer containing poorer quality water (e.g., 1000 mg/l TDS), the latter's quality would be improved over time, but the process also degrades the quality of the imported water which might have been put to some other use requiring a high water quality.

On the other hand, when poor quality water (usually wastewater from municipal or other sources) is used for recharging groundwater, it would, over time, degrade the aquifer. Because groundwater moves very slowly, the degradation could accumulate to the point that the damage would be irreversible.

Treated municipal wastewater is a potentially important source for recharging aquifers. Although the recharge process improves the quality of the effluent, its quality characteristics, and especially the reliability of effluent treatment processes, cannot be ignored as risks to groundwater quality. Municipalities constantly face the real problem of safely disposing of wastewater generated twelve months a year. The problem of waste disposal may be aptly described in a bumper sticker that states: "You can't throw it away. There is no away." California annually generates about 3.4 million acre-feet of municipal wastewater, but one survey (Ling, 1978) indicates that only 0.26 million acre-feet/year is intentionally used to recharge groundwater, mostly in southern California.

An excellent reference with chapters describing the quality aspects of wastewater used for groundwater recharge is a publication edited by Asano and Roberts (1980). Relevant chapters include: 1) Water quality criteria and standards for

groundwater recharge (Gaston); 2) Sampling equipment and techniques for monitoring groundwater during artificial recharge operations (Signor); 3) Fate of inorganic micro-contaminants during groundwater recharge (Chang and Page); 4) Pathogen removal from wastewater during groundwater recharge (Gerba); 5) Field study of organic water quality changes during groundwater recharge in the Palo Alto Baylands (Roberts et al.).

Another useful publication (Food & Agriculture Organization of the United Nations, 1979) describes: 1) types, causes, and effects of groundwater pollution and its control; and 2) methods of analysis for groundwater quality management, including a) observation well and sampling, and b) techniques for systems analysis, optimization and simulation. Scalf et al. (1981) prepared a manual of procedures for sampling groundwater quality. A more recent book, edited by Asano (1985) contains chapters by experts on the water quality and health implications of using reclaimed wastewater for groundwater recharge, including the fate of micropollutants (trace metals and trace organics) during recharge.

WATER QUANTITY

As described in the previous section on water quality, conjunctive use projects affect both surface waters (the prime source for recharge or a source that substitutes for groundwater) and subsurface waters (the recipient of recharge). The reader is again reminded of the interrelation between water quantity and quality. Increased subsurface water storage may cause increased flows of hydraulically connected streams. Whether or not the increased streamflow is beneficial is site-specific. Such an increase in base flow in the stream may alter water quality parameters such as total dissolved solids, dissolved oxygen and turbidity.

a. Surface water: It has already been pointed out that diversion of surface waters for groundwater recharge or use in lieu of pumping leaves less water in streams, rivers and deltas for meeting instream flow and flushing requirements. Bagley et al. (1985) describe the implications of accommodating instream flow needs within the appropriation system of water rights. They point out that lack of "litigation-proof" methodologies to predict tradeoffs resulting from instream flow protection has constrained legal recognition of quantifying instream requirements as part of appropriation of water from streams.

The effects on stream flow are, however, greatly reduced if releases from surface storage and diversions for groundwater recharge are made during periods of high flow in normal years and in abnormally wet years. Indeed, such diversions often prove beneficial in that the potentials for flooding and erosion are greatly diminished, provided 1) facilities exist for transporting water and recharging groundwater, and 2) there is sufficient aquifer storage capacity.

Conjunctive use is usually considered in terms of joint use of two separate water sources, surface and subsurface. In many

cases, however, the two sources are hydraulically interrelated, so that water withdrawals from an aquifer affect the flow of an overlying or nearby stream (Theis, 1941), resulting in possible environmental effects associated with the quantity of streamflow. Bittinger (1980) warned of the potential for legal confrontations because little legislation has been passed to define the rights of appropriators who obtain water from a common stream-aquifer system. He described several examples of conflicts in Nebraska, Colorado, and Kansas. For instance, computer modeling techniques predicted a flow reduction at the Overton gage on the Platte River of 125,000 acre-feet/year by 1990 because of groundwater pumping above that point.

Storage of surplus surface water in aquifers during wet periods enables utilization of the stored groundwater during dry or high-demand periods in lieu of entitled surface water rights. This leaves more of the surface water for useage in other areas and for meeting environmental instream requirements during periods of low flow.

b. Subsurface waters: Some caution, planning and forecasting is required when artificially recharging groundwater to ensure that sufficient subsurface storage space is left to accommodate storm water runoff and percolation. Failure to recharge at an appropriate time, volume and rate may cause temporary rises in the water table which could saturate the root zones, inundate sanitary landfills and cause local water quality problems.

It has already been pointed out that conjunctive use redistributes the quantity and availability of surface and subsurface water supplies. Groundwater recharge and reduced pumping affect water quantities and hydraulic gradients in aquifers, often resulting in cessation (or even reversal) of flows from one aquifer to a neighboring aquifer that was being steadily depleted before the onset of a conjunctive use project.

The water quality and saltwater intrusion aspects of such changes in subsurface hydraulic gradients were discussed in previous sections of this paper.

WILDLIFE

A growing awareness of the effects of human activities on wildlife species and their terrestrial and aquatic habitats necessitates identification of potential effects of planned conjunctive use projects, particularly since habitats are dependent on both surface and subsurface waters.

a. Terrestrial wildlife: Riparian vegetation and especially phreatophytic species, such as cottonwood, mesquite, saltcedar and willow, provide vital habitat for mammalian, bird, and insect wildlife species (Horton and Campbell, 1974). Apart from preservation of once-endangered species (e.g., white-winged and mourning doves), beekeepers point to the economic value of bee pasture (for nectar and pollen) provided in spring and early summer during the saltcedar bloom period in the arid southwest. This riparian habitat depends for moisture on the groundwater level. Therefore, changes in water table depth (lowering or raising) due to stream diversion or groundwater recharge in areas where surface (stream) and subsurface waters are hydraulically interconnected, might affect wildlife by changing or even destroying their habitat. A survey of pre-project piezometric depths and fluctuations and of habitat and wildlife species would increase the awareness of planners so as to prevent or minimize dangers to wildlife species and their habitats.

Before initiating construction of facilities, such as recharge basins, for conjunctive use it should be determined from agencies such as the Fish and Wildlife Service, Dept. of Fish and Game, and environmental groups, whether there could be temporary or permanent disruption of rare, threatened, endangered, or other sensitive species which might be in the construction area or in areas influenced by the project.

Recharge ponds attract water birds and may promote vegetative growth which could provide some feed and shelter for

wildlife. However, since maintenance of recharge ponds often includes periodic weed removal and scarifying of basins, there would be limited opportunity for developing a permanent biotic habitat.

b. Aquatic wildlife: The major concern here is when water diversions from rivers and streams reduce the quantity, quality and flow rate to such a degree that aquatic habitat for fish and organisms that are an inherent part of the food chain is temporarily or permanently damaged. General methods for collecting and analyzing water, biological and microbiological samples are described by Slack et al. (1973) and Standard Methods (1985).

The specific nature of the problem under consideration and reasons for collecting samples will dictate which aquatic communities will be evaluated and which sampling and analytical techniques will be employed. A good starting point for anyone initiating sampling in aquatic systems would be to consult the specific sections in Standard Methods (1985) for plankton, periphyton, macrophyton, macroinvertebrates, fish, amphibians, aquatic reptiles, birds and mammals. Each specific section includes (with some variation) information on sample collection, sample analysis, and interpreting and reporting results with a rather extensive reference and bibliography.

In addition, some references that are most useful for the nonspecialist in the identification of freshwater plants and animals are: 1) General introductory (aquatic ecology): Goldman and Horne (1983); 2)Algae: Prescott (1978); 3) Higher aquatic plants: Fassett (1960); 4) Invertebrates (general): Pennak (1978); 5) Protozoa: Jahn and Jahn (1949); 6) Crustaceans (general): Kaestner (1970); 7) Aquatic insects: Merritt and Cummins (1983); 8) Fishes: Eddy (1957); and 9) Amphibians: Cochran and Goin (1970).

Proper management of surface and subsurface water supplies and reservoirs would minimize adverse effects on instream requirements for aquatic wildlife. This could be achieved by ensuring that most of the diversion for offstream surface and subsurface storage is made during periods of high flow, and not at times when fish and aquatic organisms are vulnerable.

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Conjunctive use water supply refers to the coordinated use of both surface water and groundwater to meet water supply needs. There are many elements or tasks associated with conjunctive use planning. These include: hydrologic and hydraulic aspects, facilities, legal aspects, institutional arrangements, economic analysis, financial aspects and environmental effects. This document is intended as a reference to assist those involved in conjunctive use planning to more effectively and quickly focus on the necessary tasks.

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